

NASA Contractor Report 4164

NASA-CR-4164 19880016078

# F-14 Modeling Study

## *Final Report*

William H. Levison

CONTRACT NAS1-17648  
JULY 1988

LIBRARY COPY

LANGLEY RESEARCH CENTER  
LIBRARY  
HAMPTON, VIRGINIA

FOR REPT. ACL

DO NOT REMOVE FROM THIS ROOM

**NASA**



NF01819

# NASA Contractor Report 4164

## F-14 Modeling Study

### *Final Report*

William H. Levison  
*BBN Laboratories Incorporated*  
*Cambridge, Massachusetts*

Prepared for  
Langley Research Center  
under Contract NAS1-17648



National Aeronautics  
and Space Administration

Scientific and Technical  
Information Division

1988

# Table of Contents

<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Objectives	1
1.2 Review of the Phase 1 Effort	2
1.3 The NT-33A Study	3
1.4 Organization of this Report	4
<b>2. ANALYSIS PROCEDURES</b>	<b>5</b>
2.1 Statistical Analysis of Tracking Performance	5
2.1.1 Closed-Loop Performance Metrics	5
2.1.2 Frequency-Response Metrics	5
2.2 Model Analysis	7
<b>3. Principal Results</b>	<b>11</b>
3.1 Closed-Loop Performance Measures	11
3.2 Frequency-Response Measures	20
3.3 Nonlinear Analysis	25
3.3.1 Visual Inspection of Time Histories	25
3.3.2 Statistical Analysis of Stick-Rate Amplitude	30
<b>4. Discussion</b>	<b>37</b>
<b>5. References</b>	<b>41</b>
<b>APPENDIX A.</b>	<b>43</b>

## List of Figures

<b>Figure 3-1:</b>	Effects of Delay and Simulator Mode on SD Performance Scores, Roll Axis	12
<b>Figure 3-2:</b>	Effects of Delay and Simulator Mode on SD Performance Scores, Pitch Axis	13
<b>Figure 3-3:</b>	Effects of Delay on Single- and Combined-Task SD Performance Scores, Roll Axis	15
<b>Figure 3-4:</b>	Effects of Delay on Single- and Combined-Task Performance Scores, Pitch Axis	16
<b>Figure 3-5:</b>	Effects of Delay on SD Performance Scores for Disturbance Regulation, Roll Axis	18
<b>Figure 3-6:</b>	Effects of Delay on SD Performance Scores for Disturbance Regulation, Pitch Axis	19
<b>Figure 3-7:</b>	Effects of Dynamics on Pilot Frequency Response, Roll Axis	21
<b>Figure 3-8:</b>	Effects of Dynamics on Pilot Frequency Response, Pitch Axis	22
<b>Figure 3-9:</b>	Effects of Delay on Pilot Frequency Response, Roll Axis	23
<b>Figure 3-10:</b>	Effects of Delay on Pilot Frequency Response, Pitch Axis	24
<b>Figure 3-11:</b>	Effects of Simulator Mode on Pilot Frequency Response, Roll Axis	26
<b>Figure 3-12:</b>	Effects of Simulator Mode on Pilot Frequency Response, Pitch Axis	27
<b>Figure 3-13:</b>	Time Histories for Pilot A	29
<b>Figure 3-14:</b>	Time Histories for Pilot B	31
<b>Figure 3-15:</b>	Probability Densities for Simulated Stick Rate	34
<b>Figure 3-16:</b>	Probability Densities for Experimental Stick Rate	35

## List of Tables

<b>Table 2-1:</b> Independent Parameters Adjusted During the Model analysis	8
<b>Table 3-1:</b> Effects of Experimental Factors on Average Performance Ratios	14
<b>Table 3-2:</b> Independent Model Parameters	28
<b>Table 3-3:</b> Amplitude Statistics for Stick Rate	33
<b>Table A-1:</b> Experimental Roll-Axis SD Scores	44
<b>Table A-2:</b> Experimental Pitch-Axis SD Scores	45
<b>Table A-3:</b> Model-Generated Roll-Axis SD Scores	46
<b>Table A-4:</b> Model Predicted Pitch-Axis SD Scores	47

**This Page Intentionally Left Blank**

## PREFACE

This work was performed by BBN Laboratories (BBN) for the National Aeronautics and Space Administration (NASA) under contract No. NAS1-17648. Drs. Sheldon Baron and Dr. William H. Levison served respectively as Principal Investigator and Project Engineer for BBN; Mr. Burnell McKissick was the NASA Technical Monitor.

Some of the analysis reported herein was supported, in part, by the Calspan Corporation under Purchase Order No. 78932, Air Force Contract No. F33615-83-C-3606.

# 1. INTRODUCTION

## 1.1 Objectives

Both the military and civilian segments of aviation are placing an increasing reliance on flight simulators for aircraft research and development and for pilot training and proficiency maintenance. Because of the increasing sophistication and associated costs of available simulation devices, issues relating to trade-offs between simulation fidelity and costs have risen to highly visible levels. When determining the simulator configuration to meet a specific goals, the designer must consider the need for particular cueing devices as well as the requisite level of fidelity, and he should understand the constraints placed upon man-machine system performance (including performance/workload trade-offs), as well as costs, imposed by that level of simulation fidelity.

To address these issues, NASA-LaRC undertook a combined experimental and analytical program to develop data and methodologies for the evaluation and specification of simulator validity and fidelity. The experimental program involved ground-based simulator experiments at NASA-LaRC facilities and in-flight tests, using an "F-14" aircraft, performed at Edwards Air Force Base. BBN's role in this effort was to first analyze the simulator results with the aid of the optimal control model (OCM) for pilot-vehicle systems for the purposes of (1) "calibrating" the model as required for the subject pool and task environment, and (2) providing an analytic explanation for performance differences, if any, among the cuing conditions explored in the simulation. This analysis was to be followed by an analysis of the in-flight tests, again with the goal of using the model to provide an analytic framework for whatever performance differences might be found between ground-based and in-flight performance.

A substantial portion of BBN's effort was devoted to obtaining an accurate and workable linear model of the simulated air-to-air combat task. The plan of attack described above was not completed because of difficulties encountered in the production of the NASA data base, particularly with respect to the in-flight tests. During the contract performance period, however, the Calspan Corporation provided BBN with a data base obtained from a combined ground-based and in-flight simulation study of simulator fidelity using an NT-33A variable-stability aircraft.<sup>1</sup> Given this situation, the best available course of action in support of the goals of the contract was to perform model analysis of the NT-33A data base.

---

<sup>1</sup>Calspan Corporation, Air Force Contract No. F33615-83-C-3606



In effect, BBN's effort under the NASA contract was conducted in two phases: (1) model development and data analysis relevant to the NASA simulation study, and (2) analysis of the NT-33A data base. The Phase 1 effort has been described in an interim report (Levison and Baron, 1984) and in subsequent progress reports. The results of this phase are summarized briefly below; the bulk of this report is devoted to a summary of the Phase 2 effort.

## 1.2 Review of the Phase 1 Effort

The task explored in the NASA simulation and in-flight tests involved an "F-14" aircraft tracking a target aircraft executing a 3g wind-up turn. Once steady-state undisturbed tracking was achieved, the vertical displacement of the reticle (sight) of the pursuing aircraft was disturbed by a random appearing signal. The simulator experiments duplicated this task under a variety of cuing conditions. Data were obtained using two ground-based simulators: the moving-base Visual Motion Simulator (VMS) and the fixed-base Differential Maneuvering Simulator (DMS). Four experimental conditions were explored in each simulator: with and without "motion", and with and without g-seat cuing. The "motion" condition represented whole-body motion cuing in the VMS and helmet-loading in the DMS. The same subjects performed in both simulators as well as in the "F-14".

As noted above, much of the Phase 1 BBN effort was devoted to formulating a model of the air-to-air tracking task, including (1) modeling the target kinematics, (2) developing the linearized line-of-sight equations, (3) reducing the dimensionality of the overall model, (4) validating the math model against the NASA simulation, and (5) performing a sensitivity analysis with the model to explore the effects of assumptions concerning the simulator and/or the pilot. These results have been summarized by Levison and Baron (1984).

Statistical analysis of the tracking scores obtained in the NASA simulation studies revealed the following general trends.

- Effects of non-visual cuing ("motion" or "g-seat") were neither large nor statistically significant.
- Differences across subjects were relatively large and statistically significant.
- Although not found to be statistically significant, the VMS/DMS differences in lateral-axis LOS errors were relatively large.

The lack of differences across cuing conditions is consistent with post-experiment model analysis which showed a predicted lack of sensitivity of line-of-sight tracking error to the presence of motion cues (Baron and Levison, 1984).

### 1.3 The NT-33A Study

The major objective of the NT-33A study was to explore the effects of control system delays on closed-loop performance in ground-based and in-flight simulations of an attitude tracking task. Pre-experiment model analysis was performed by BBN to help specify certain experimental variables: primarily, parameters of the external forcing functions to be used in the steady-state tracking segments of the NT-33A simulations. The pre-experiment analysis has been documented by Levison and Papazian(1986); major predictions yielded by this analysis were:

1. modest increases in tracking error score with increasing delay,
2. larger delay effects for the generic high-performance fighter flown aggressively ("F-16") than for the generic heavy transport ("C-141") flown in a more relaxed manner,
3. relatively small differences (less than 10%) between performance in-flight and in the ground-based simulations, and
4. similar relative effects of experimental variable on performance in the pitch and roll axes.

As shown in this report, these pre-experiment predictions were largely confirmed by the manned simulation experiments.

Post-experiment analysis included statistical analysis of steady-state tracking performance metrics and model analysis using the same optimal control model (OCM) employed earlier in the study. The reader is assumed to be familiar with the structure and application of this model. The major objectives of the model analysis were to help explain any differences that might arise between experimental results and the results predicted by pre-experiment analysis, and to explore the utility of the OCM as a potential tool for interpolating the results of simulation experiments designed to explore time delay effects.

A subset of the NT-33A experimental conditions was analyzed by BBN. Pitch- and roll-axis performance in single-axis target-tracking tasks was analyzed for the following combinations of experimental variables: (a) "F-16" and "C-141" aircraft dynamics, (b) zero and 180 msec simulation delay added to the irreducible simulation delay of about 100 msec, and (c) ground-based and in-flight simulations. In addition, the combined-axis performance in roll and pitch were analyzed for the following combination of experimental variables: (a) "F-16" and "C-141" dynamics, (b) zero and 180 msec added delay, and (c) target and disturbance inputs. In-flight performance for combined-axis tasks was not analyzed by BBN because data were not available for all test pilots.

"Single-axis" tasks were tasks in which an external forcing function was applied to either the roll or the pitch axis, but not both. Forcing functions were applied to both axes in the "combined-axis" tasks. In all cases, the pilot was required to control both the pitch and roll axes.

## **1.4 Organization of this Report**

The remainder of this report presents the results of the analysis performed by BBN on the NT-33A data. Procedures used in performing both statistical analysis and model analysis on the experimental data are reviewed in Chapter 2. Major results are presented in Chapter 3, and the discussion provided in Chapter summarizes these results, outlines a procedure for a combined analytical and experimental approach to studying simulator fidelity issues, and suggests areas of further study aimed toward development and validation of this approach.

## 2. ANALYSIS PROCEDURES

### 2.1 Statistical Analysis of Tracking Performance

Means and standard errors were obtained for closed-loop performance metrics and for pilot frequency response measures as described below.

#### 2.1.1 Closed-Loop Performance Metrics

Primary data reduction was performed by Calspan; BBN performed the subsequent averaging across replications and across subjects. Within-trial mean and standard-deviation (SD) scores were first computed for all important problem variables. These scores were then averaged across the two replications/subject to provide average performance measures for each subject for each of the experimental conditions considered in the BBN analysis. Finally, population means and estimated standard errors of the population means were computed for each condition of interest. The summary statistics reported later in this report are the means and standard errors of the SD scores for tracking error, control force, and control force-rate.

#### 2.1.2 Frequency-Response Metrics

Pilot frequency-response metrics consisted of the describing function -- shown as "gain" (more properly, "amplitude-ratio") and phase-shift" curves, and curves of the pilot's "remnant" (the spectral density of that portion of the pilot's control or "stick" force that is not linearly correlated with the external forcing function).

It was originally intended that analysis techniques appropriate to sum-of-sines (SOS) inputs would be employed (Zacharias and Levison, 1979). Because the nominal SOS input used in this study had significant power at off-nominal input frequencies (i.e. "sideband power"), the analysis technique was modified to be appropriate to inputs continuous in frequency. Specifically, the pilot's describing function was estimated at each nominal SOS frequency as:

$$H = \frac{\overline{UI^*}}{\overline{EI^*}}$$

where H is the describing function expressed as a complex number, and I, E, and U are the Fourier coefficients of the external input, the tracking error, and pilot's control response, respectively, obtained from fast-Fourier analysis. The overstrike signifies averaging of the cross-power terms over a frequency range of approximately 1/4 octave centered about the nominal SOS frequency.

The remnant power was computed in the vicinity of each SOS input frequency as:

$$\text{Remnant} = \overline{|U|^2} - \frac{|\overline{UI^*}|^2}{\overline{|I|^2}}$$

Because of the significant amount of pilot remnant, intra- and inter-subject averaging of the describing functions was performed using techniques recently developed to maximize the reliability of the averaging process (Levison, 1985). Individual describing function as defined above were not averaged; instead, averaging was performed on the cross-power quantities, first across replications and then across subjects. The inter-subject average describing function was then computed as shown in Equation 1, where the numerator and denominator terms now represent inter-subject averages. The resulting complex number H was then converted to equivalent gain and phase shift.

Because phase shift is defined only within a cycle, the OCM was used to generate a theoretical reference curve to "unwrap" the phase curve. This unwrapping procedure has been described by Levison, Junker, and Kenner (1985).

Estimated standard errors of the mean gain and phase shift were computed from the variability of the cross-power spectral measures as described by Levison (1985). Inter-subject statistics on the remnant estimates were obtained via the same procedures adopted for the closed-loop performance metrics.

## 2.2 Model Analysis

A major objective of the model analysis was to explore the potential of the OCM as a tool for interpolating the results of manned simulations, rather than to obtain the best curve fit possible. Therefore, independent "pilot-related" model parameters were not subjected to the type of unrestricted gradient search identification procedure that has been used appropriately in the past for quantifying operator capabilities (Levison, 1981). Instead, model analysis was initiated with parameters selected from previous laboratory studies, and subsequent parameter changes were made only as required to provide an acceptable subjective match to the data for certain baseline conditions. Predictions were then obtained for other experimental conditions with no further changes in pilot-related parameters.

In order to maximize computational efficiency, most of the model analysis was conducted to provide comparisons with the average performance of the three test pilots. There were substantial inter-subject differences however, and some analysis was conducted to explore these differences.

In this section of the memo we describe the procedure by which independent model parameters were selected. Interpretation of the specific values selected is provided in Chapter 4.

Non-zero values were assigned to the following pilot-related model parameters:

- Motor Time Constant. This parameter reflects bandwidth limitations imposed by the pilot/stick interface. Values on the order of 0.09 to 0.13 seconds are typical for force sticks and optimal control gains. Larger values have been found for sticks having significant displacement characteristics (Repperger and Levison, 1984).
- Operator Delay. A pure transport delay is associated with the operator's response characteristics. This OCM independent parameter is generally not influenced by the tracking task; a value of 0.2 seconds is typical. When the tracking task contains display-related delays that show up in the computation of the pilot describing function, such delays should be included in the "operator delay" to allow a meaningful comparison of measured and predicted operator phase shift. For this study, operator delay was fixed at 0.22 seconds -- 0.20 for the operator and 0.02 for display delay.
- Penalty on Control Force. For tasks in which the control gain is optimal, there is generally no need to assign a performance penalty (i.e., a non-zero "cost coefficient" in the quadratic performance index) to control force or displacement. Where significant forces are required, however, a specific penalty associated with control force (or possibly control rate) improves the match to operator performance (Levison, 1984). The control penalty is expressed here as the numerical value of the control SD score that contributes one unit of cost to the performance index. (Note: one unit of cost is assigned to an SD score of 1 degree for roll or pitch tracking error.)
- Residual Noise on Error Perception. The OCM allows the user to specify a "residual noise" standard

deviation for each of the perceptual variables used by the pilot to reflect the effects of threshold-like phenomena such as perceptual resolution limitations and "indifference thresholds". Residual noise is usually set to zero for laboratory tracking tasks that use symbolic displays with optimal display gains. In general, however, nonzero residual noise should be specified for non-ideal perceptual environments such as real-world visual scene cues (Levison and Warren, 1984), or when the operator is indifferent to errors below a certain level.

- **Observation Noise Ratio.** Pilot remnant is modeled largely as an observation (perceptual) noise process. Except for the residual noise term, observation noise is assumed to scale with the rms value of the perceived variable. An "observation noise ratio" of around -20 dB is typical for laboratory experiments. Based on the results of a recent laboratory study of time-delay effects (Levison and Huggins, 1986), this parameter was fixed at -19 dB for this analysis.
- **Motor Noise Ratio.** Except for tasks using very large control sensitivities, or human operators with substantial neurological "tremor", this term is negligible. It was fixed at -90 dB for this analysis.
- **Internal Motor Noise Ratio.** To reflect certain limitations on the operator's ability to predict the effects of his control input on vehicle response, we assign a small but non-negligible value to the "internal" motor noise (i.e., the pilot's perception of his motor noise variance). This parameter was fixed at -44 dB based on the Levison and Huggins study.

Three pilot-related parameters were varied during the course of this analysis: motor time constant, the control penalty, and residual noise on tracking error. The remaining parameters were kept fixed as described above.

For the purposes of model analysis, the "baseline" condition was defined as single-variable tracking, target input, ground-based simulation, zero added delay. There were thus four experimental baseline tracking tasks: pitch and roll, "F-16" and "C-141". The approach to model analysis was to first obtain two "calibration" sets of independent model parameters -- one providing the best joint match to "F-16" and "C-141" performance in roll, and one providing a joint match to pitch-axis performance for the baseline conditions. With parameters held fixed at the appropriate baseline values, predictions were then obtained for (1) the effects of additional delay on performance, and (2) performance differences between ground and in-flight simulation.

Values used in the pre-experiment analysis -- shown in the first column of Table 2-1 -- were used in an initial attempt to match the roll-axis data. These values proved to be too optimistic in terms of predicting average performance. In particular, the experimental tracking errors scores were substantially larger than predicted, the control scores were lower than predicted, and the remnant was greater than predicted.

**Table 2-1: Independent Parameters Adjusted During the Model analysis**

Parameter	Initial	Roll	Pitch
Motor Time Constant, sec	0.12	0.20	0.15
Control for Unit Cost, pounds	0.	0.	20.
Rms Residual Noise, degrees	0.	75.	2.25

The predicted control and control-rate scores were brought into general agreement with the data by increasing

the motor time constant to 0.20 seconds. This action had the additional effect of increasing the predicted tracking error score, but not by the amount needed to match experimental results.

Examination of the performance of individual test pilots showed substantial inter-subject differences. Pilot A was the best performer in terms of minimizing the roll-error SD score; his performance could be matched with values near those initially selected. As noted above, considerations of efficiency dictated that the bulk of the analysis be performed on average performance, and the discussion here is relevant to average performance. Later in this report we document some of the inter-subject differences.

One or more model parameters related to pilot remnant had to be modified to provide better matches to experimental tracking error scores and remnant spectra. Increasing the observation noise tended to provide a better match to the remnant at mid and high frequencies, whereas including the residual noise improved the match at low frequencies. Both methods were initially explored, but the residual-noise adjustment seemed to provide slightly better predictive capabilities and is therefore the method that was pursued.

A residual noise of around 75 degrees was required to provide an acceptable match to the baseline data (i.e., predicted SD scores within 10-15% of the experimental scores) for the roll axis. This value was much larger than would be needed to accommodate an indifference threshold of 5 degrees that one might infer from the instructions to the test pilots. As we show later in this report, this large value might reflect, in part, significant nonlinearities in the pilot's response behavior.

The pitch-axis baseline tasks were then modeled. The motor time constant of 0.2 seconds obtained in the roll-axis match was reduced to 0.15 to provide a better match to the control and control-rate scores, and the residual noise was readjusted to match tracking error. Introduction of the control penalty for the pitch-axis task provided a somewhat better match to the "F-16"/"C-141" performance differences. (A subsequent re-analysis of the roll-axis task showed that the same control penalty had negligible effect on predicted roll-axis performance.)

Once calibrated for the baseline tasks, the pilot-related model parameters considered above were held fixed as the effects of experimental variables were predicted. Changes in experimental conditions were modeled as follows:

- Vehicle delay. The addition of delay to the simulated vehicle's control-system delay was modeled by simply incrementing the "vehicle delay" parameter of the OCM by the same amount. (A baseline vehicle delay of 0.08 seconds was included to reflect irreducible simulator delays exclusive of display-related delay.)
- Ground/flight differences. The parameterization defined above pertains to the ground-based simulation. To account for the effects of in-flight simulation, display variables associated with perception of whole-



body motion cues were assigned fractional attentions of unity. These variables were vehicle roll rate and roll acceleration for roll-axis tracking, and vehicle pitch rate, pitch acceleration, and normal acceleration for pitch-axis tracking.

Combined-axis tracking. Implicit in the parameterization defined above is the assumption that the pilots could devote nearly full attention to the control axis containing the external forcing-function for the single-axis tasks. For combined-axis tracking, we assume that the pilot's must allocate attention in roughly equal proportions to the pitch- and roll-axis tracking tasks. Combined-axis tracking was therefore modeled by increasing the observation noise ratio by 3 dB (equivalent to assigning fractional attentions of 0.5 to all perceived variables).

### 3. Principal Results

The results of the statistical and model analysis are presented together in this chapter. Results are organized as follows: (1) closed-loop performance metrics, (2) frequency-response measures, and (3) nonlinear analysis of selected time histories.

#### 3.1 Closed-Loop Performance Measures

Means and standard errors for tracking error, stick force, and stick force rate SD scores are tabulated in the appendix for the conditions analyzed by BBN. Also tabulated are the corresponding model predictions.

Effects of added delay and simulator mode on measured and predicted SD scores are shown in Figure 3-1 for the roll-axis task and in Figure 3-2 for the pitch-axis task. These results pertain to single-axis target-following tasks.

The trends of the tracking error scores were generally as predicted by the pre-experiment model analysis (and confirmed by the post-experiment model analysis shown in the figures):

- Addition of 180 msec delay produced a modest increase in the SD score.
- Delay effects are relatively greater for the "F-16" dynamics than for the "C-141".
- Ground-base simulation produced somewhat larger error scores than in-flight simulation, but the effects of simulator mode on performance were less than the effects of control-system delay for the delays considered in this analysis.

As in a previous study of time-delay effects (Levison and Huggins, 1986), the model tended to slightly underestimate the relative increase in error due to added delay. Model/data discrepancies of this sort were, however, within the experimental standard error and cannot be considered statistically significant.

The largest model-data discrepancy concerning tracking error scores -- the only difference likely to be statistically significant -- occurred for "F-16" pitch-axis tracking (Figure 3-2a), where the model underestimated differences between in-flight and ground simulator performance. This trend has been seen in some previous experiments in which the benefits of whole-body motion cuing have not been fully accounted for by the kind of simple informational treatment conducted here (Levison, Lancraft, and Junker, 1979). Ground/flight differences for the remaining error scores ("C-141" pitch, "F-16" and "C-141" roll), however, are predicted rather closely.

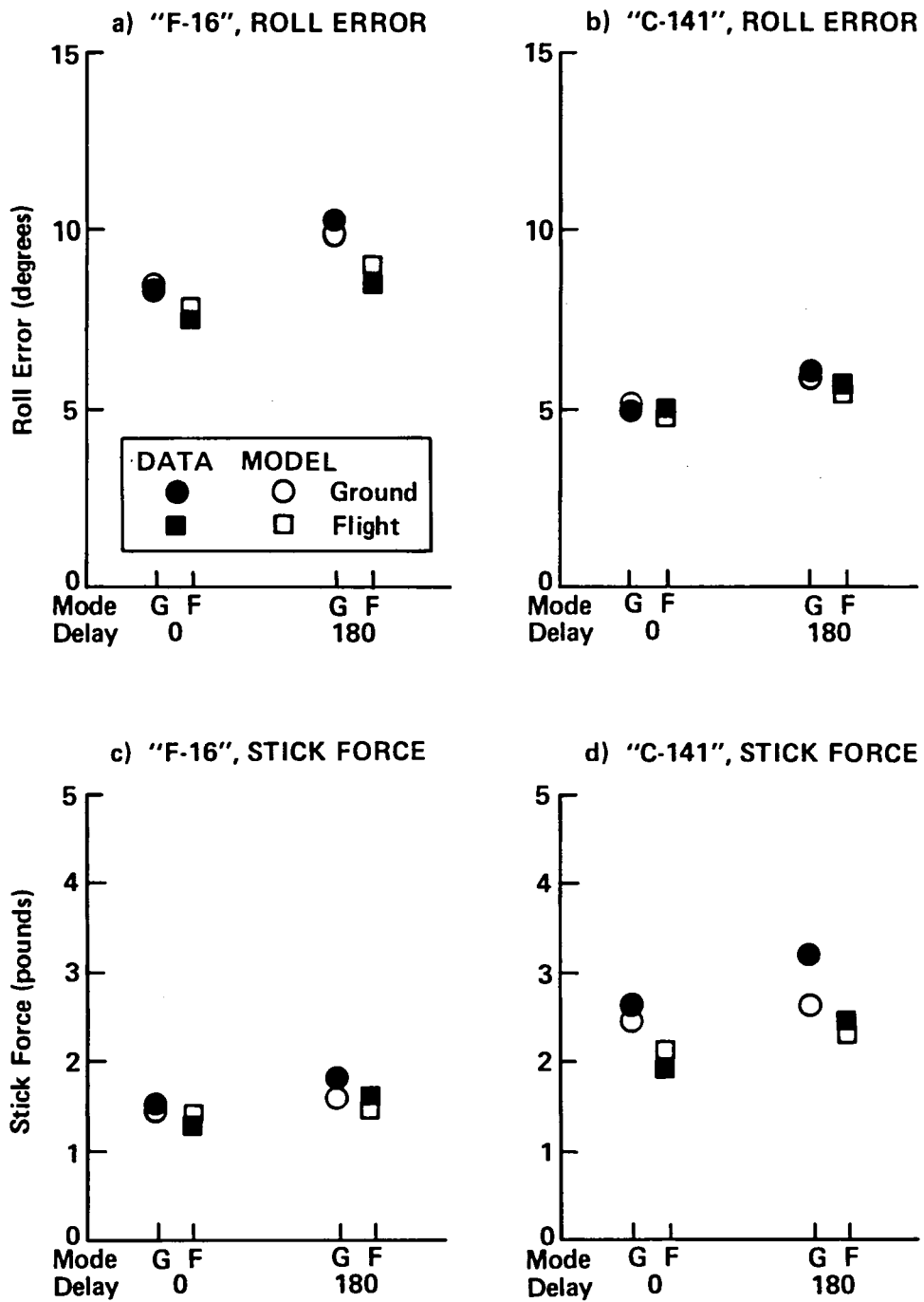
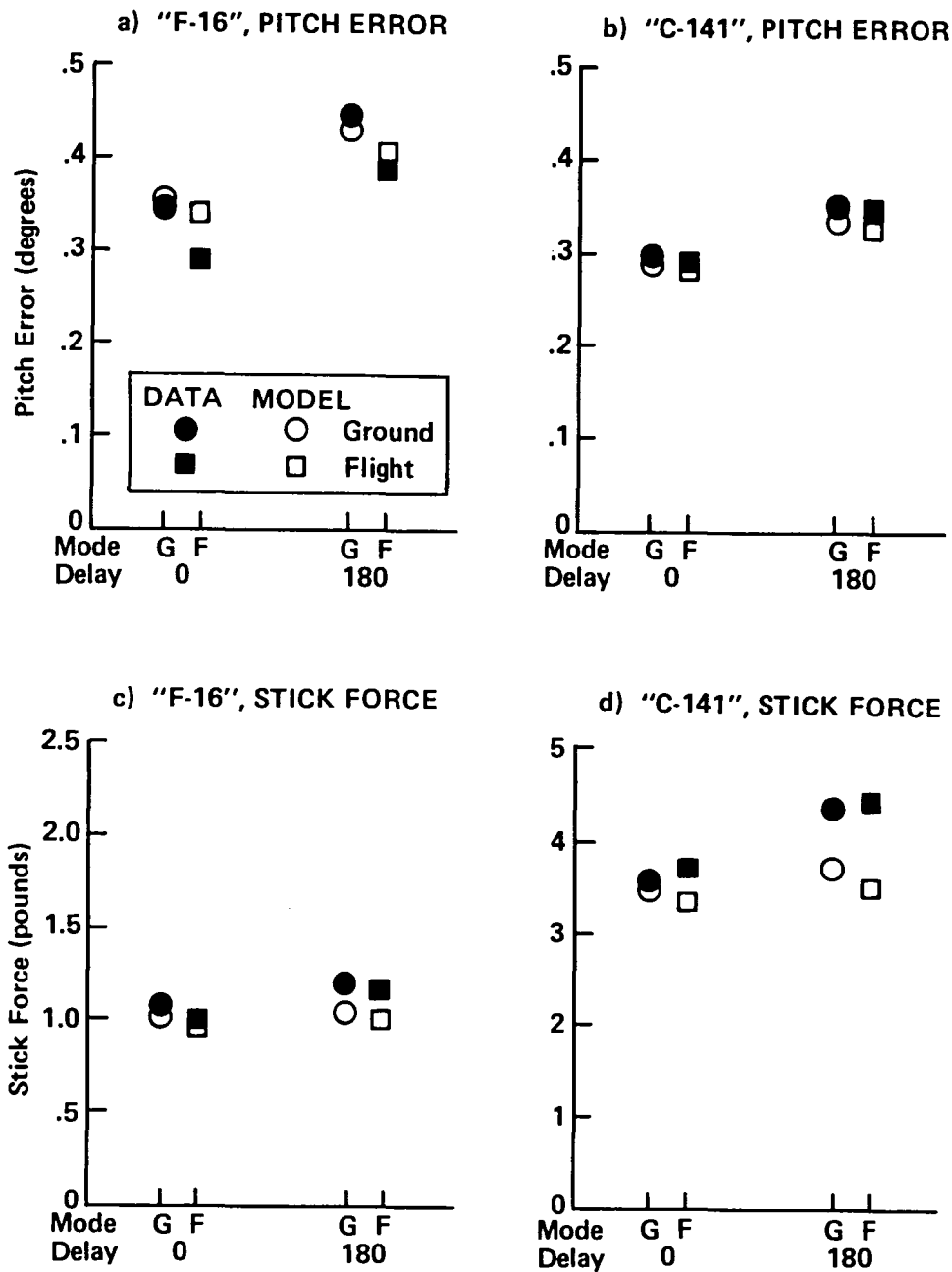


Figure 3-1: Effects of Delay and Simulator Mode on SD Performance Scores, Roll Axis

Target-tracking task.

Average of 3 subjects, 2 replications/subject.

G = ground-base, F = in-flight.



**Figure 3-2: Effects of Delay and Simulator Mode on SD Performance Scores, Pitch Axis**  
**Target-tracking task.**  
**Average of 3 subjects, 2 replications/subject.**  
**G = ground-base, F = in-flight.**

Figure 3-1c and 3-2c show little measured or predicted effects of experimental variables on the stick SD score for "F-16" tasks. Effects of both delay and simulator mode are apparent in the "C-141" experimental data (Figures 3-1d and 3-2d). The model mimicked the noticeable mode difference for the "C-141", zero-delay roll-axis task, but it did not predict the observed effects of delay on the "C-141" stick score.

Table 3-1 provides a quantitative summary of the relative effects of the experimental factors of control-system delay and simulator mode. Entries under the "delay" heading were obtained by taking the ratio of the population-average error SD score for the 180-msec condition to the average error score for the zero-delay condition. Each entry in the table is the average of four such ratios (pitch and roll, ground and flight). Similarly, entries under the "simulator mode" heading were obtained by averaging the ratios of the "ground" error scores to the "flight" error scores, averaged over the two axes and the two delay conditions. All data in this table pertain to the single-axis, target-tracking tasks.

**Table 3-1: Effects of Experimental Factors on Average Performance Ratios**

	Delay		Simulator Mode	
	"F-16"	"C-141"	"F-16"	"C-141"
<b>Data</b>	1.25	1.21	1.18	1.03
<b>Model</b>	1.19	1.15	1.06	1.06

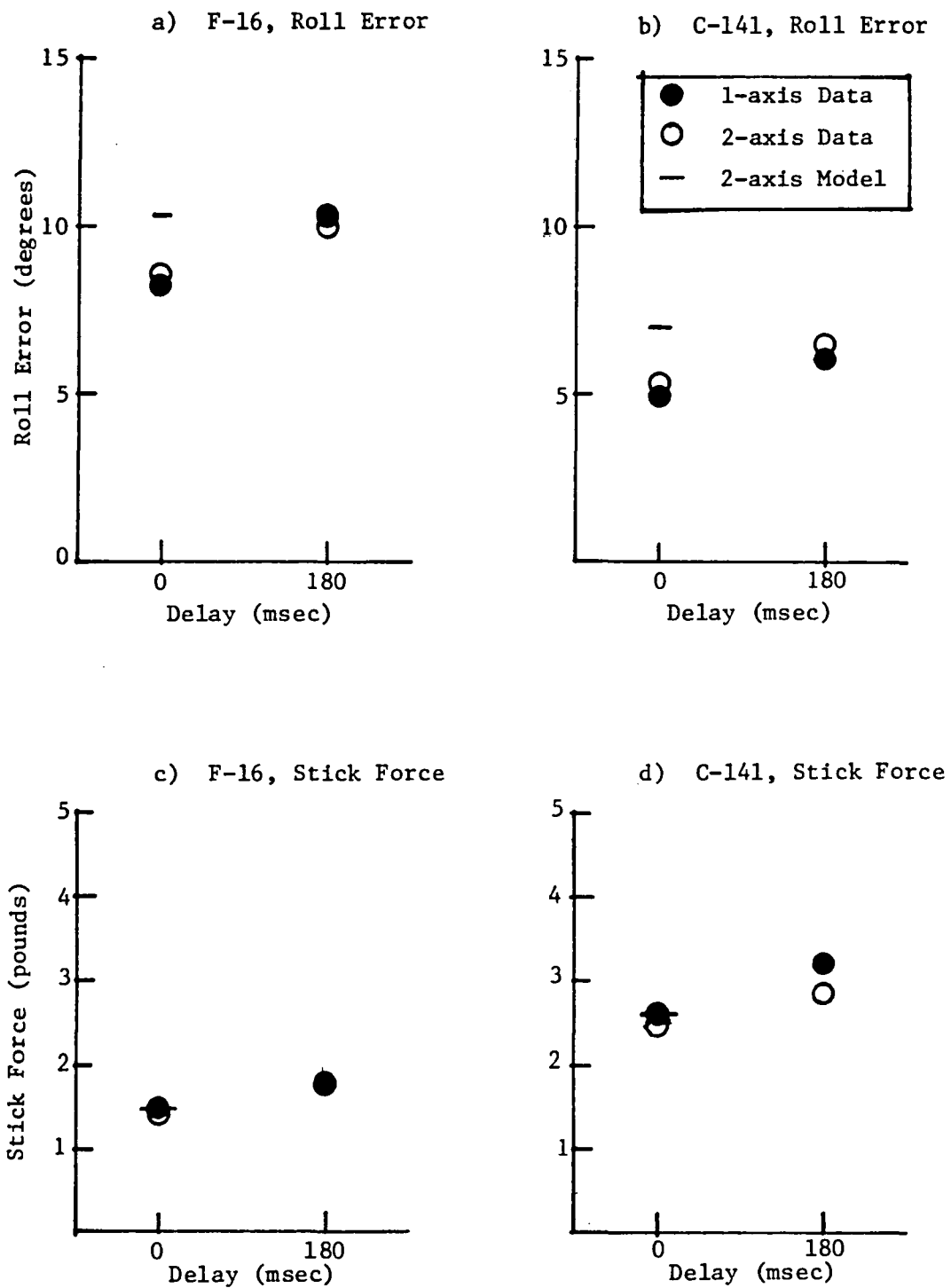
**Averaged over single-axis, target-tracking tasks.  
Three subjects, two replications/subject.**

Table 3-1 confirms the qualitative impressions obtained from Figure 3-1 and 3-2. In terms of the proportional increase in tracking error scores, the addition of 180 msec delay had a greater effect than the transition from flight to ground, and the effects of delay were slightly greater for the "F-16" than for the "C-141". The model replicated these trends, although it did not predict the full extent of the delay effects.

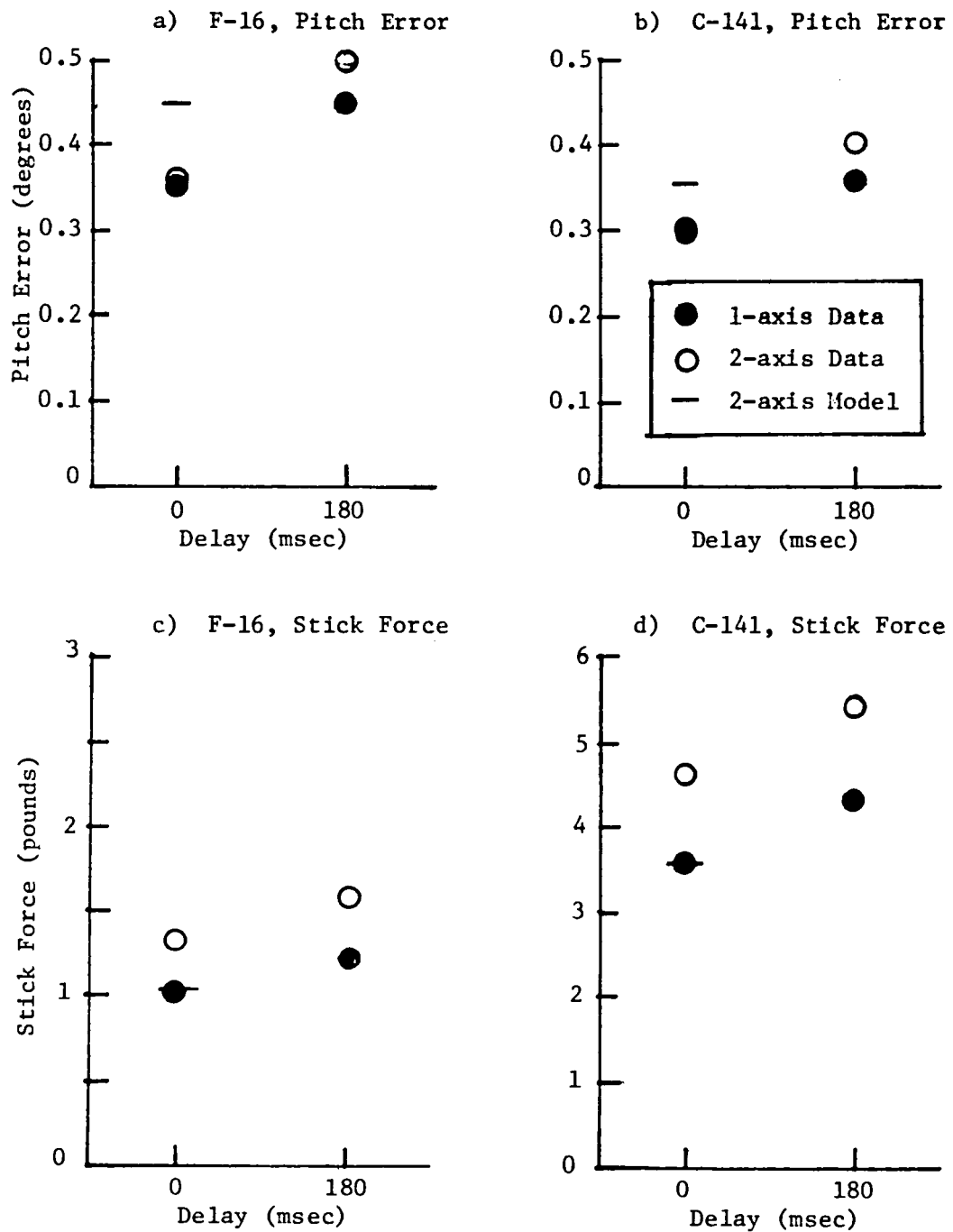
Comparisons of experimental single- and combined-task performance for the zero and 180-msec delay conditions are provided by Figures 3-3 and 3-4 for roll and pitch performance, respectively. Also shown are model predictions for the 2-axis, zero-delay conditions.

Combined-task performance scores for the roll-axis were nearly identical to the single-task scores. Inspection of the standard errors provided in Table A-1 of the Appendix suggests that the small differences shown in Figure 3-3 were not statistically significant.

Taskloading had a more pronounced effect on pitch-axis performance. Figure 3-4 shows that combined-axis



**Figure 3-3: Effects of Delay on Single- and Combined-Task SD Performance Scores, Roll Axis**  
**Target-tracking task.**  
**Average of 3 subjects, 2 replications/subject.**



**Figure 3-4: Effects of Delay on Single- and Combined-Task Performance Scores, Pitch Axis**  
**Target-tracking task.**  
**Average of 3 subjects, 2 replications/subject.**

stick scores were 25% to 35% greater than single-axis scores for both dynamics and delay conditions. Effects of taskloading on pitch error was less consistent. The error scores for the zero-delay conditions were the same for the 1- and 2-axis tasks, but the addition of 180 msec delay caused larger performance degradations for the combined-axis tasks.

The horizontal bars in Figure 3-3 and 3-4 show that the model overestimated the differences between combined-task and single-task performance, predicting differences in the error SD score on the order of 20% to 30% when, in fact, experimental differences were negligible. Because of the clear discrepancy between model and data with regard to taskloading effects, model analysis was not performed for the 180-msec delay condition.

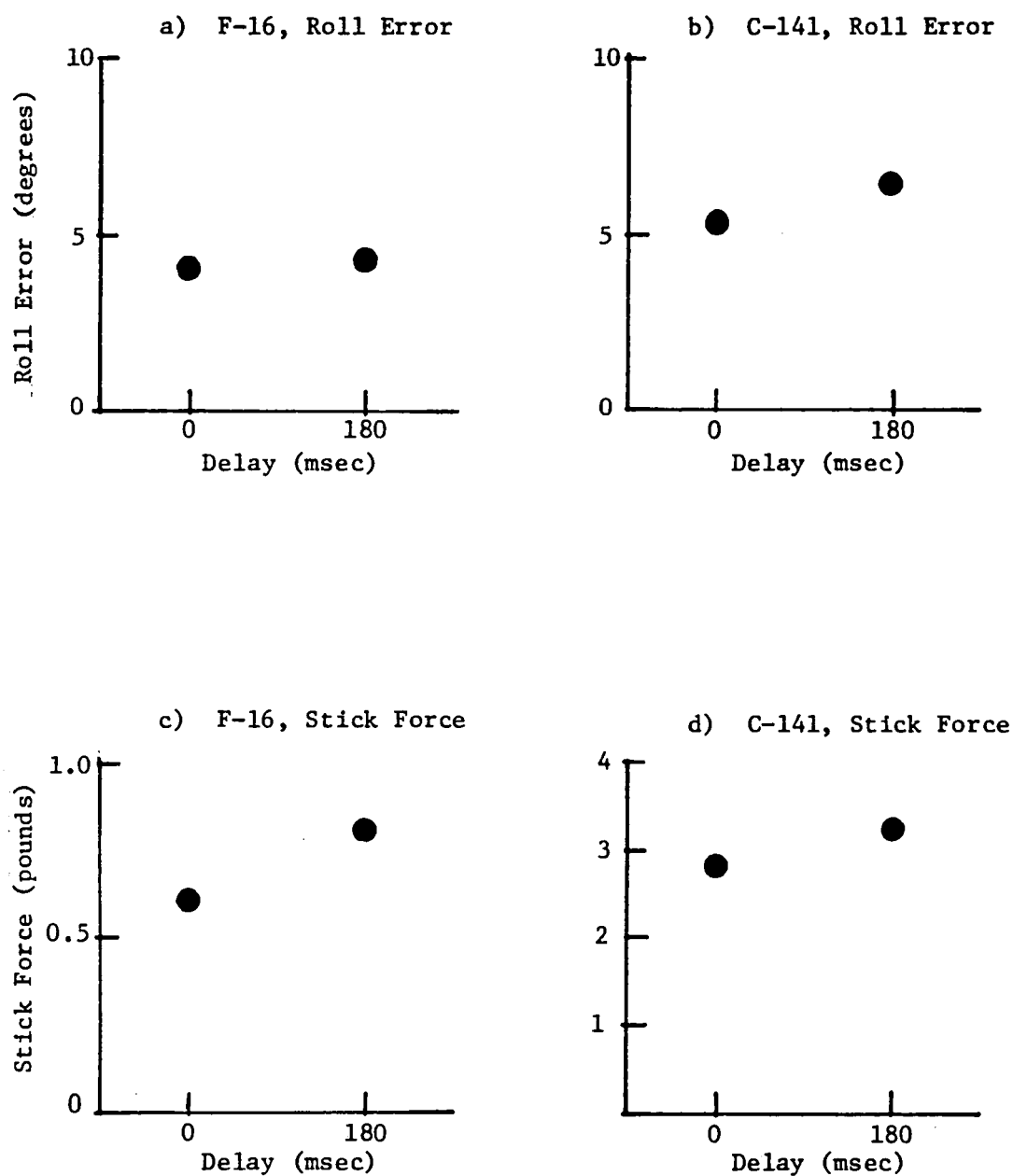
The tendency of the model to predict taskloading effects on tracking error when none were found experimentally does not signify a structural defect of the OCM, but it does suggest a slight revision in the procedure for selecting pilot parameters. Discussion of this issue is deferred to Chapter 4.

Effects of system delay on combined-task disturbance-regulation scores are shown in Figures 3-5 and 3-6 for roll and pitch, respectively. Although contract resources did not allow modeling of the disturbance tasks, comparisons of experimental results can be made to the pre-experiment model predictions documented by Levison and Huggins (1986).

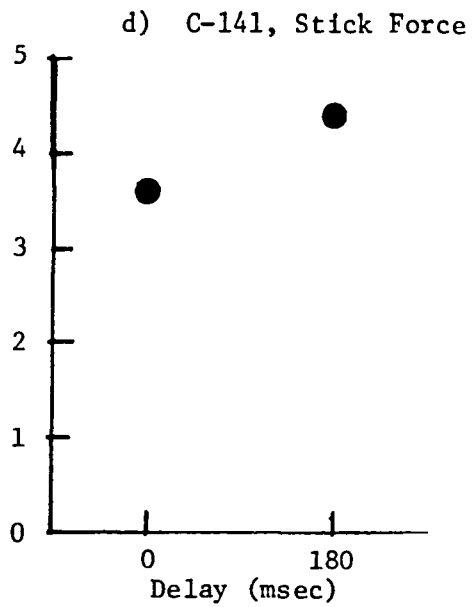
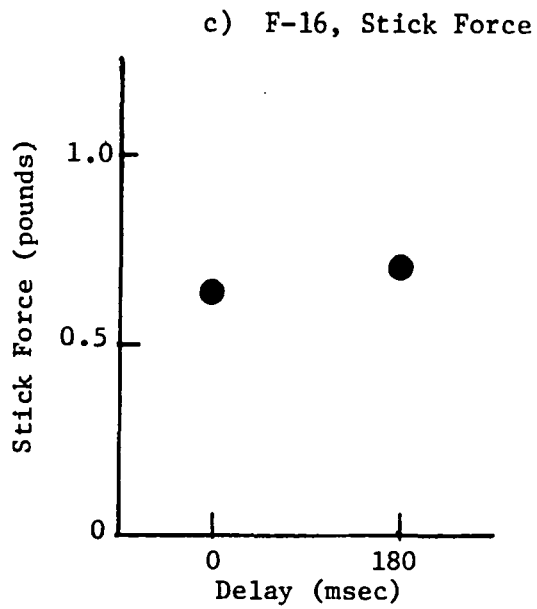
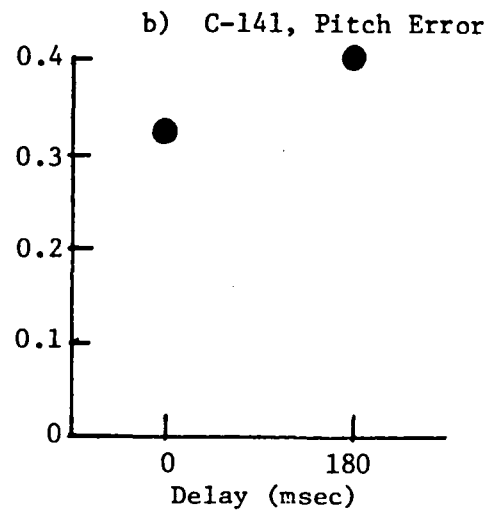
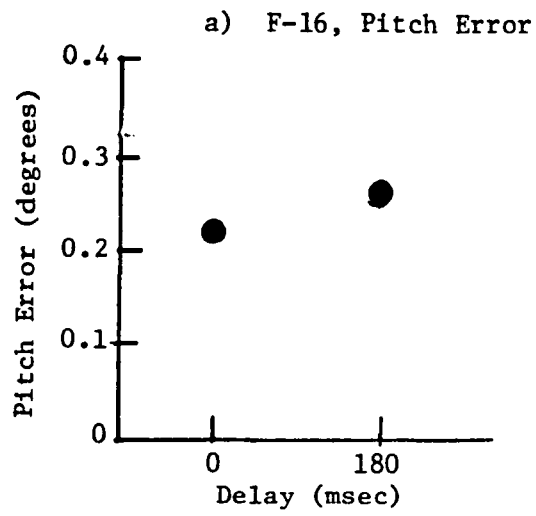
As predicted by the model, the effect of delay on "C-141" tracking error was about the same for the disturbance-regulation task as for the target-following task. The trend of the "F-16" results was the reverse of that predicted, however. Pre-experiment model analysis indicated that delay would have a substantially smaller effect on pitch-axis performance than on roll-axis, whereas the experimental data showed the opposite trend. Two factors may account for this model/data discrepancy: (1) the pre-experiment model analysis was not conducted with independent parameters that provided the best match to the baseline data, and (2) the forcing functions applied experimentally differed in certain respect from those assumed for the initial model analysis. Additional model analysis of the disturbance-tracking results would be needed to resolve this apparent discrepancy for the "F-16" task.

Discussion of the model has concentrated largely on the effects of delay and taskloading. It should also be noted that the OCM accounted for performance differences between the two simulated aircraft that were considered in the BBN analysis.





**Figure 3-5: Effects of Delay on SD Performance Scores for Disturbance Regulation, Roll Axis**  
**Average of 3 subjects, 2 replications/subject**



**Figure 3-6: Effects of Delay on SD Performance Scores for Disturbance Regulation, Pitch Axis**  
**Average of 3 subjects, 2 replications/subject.**

## 3.2 Frequency-Response Measures

Figures 3-7 through 3-12 show the effects of three experimental variables (dynamics, delay, and simulator mode) on pilot frequency response. Discrete symbols and smooth curves indicate experimental data and model results, respectively. A gain of 0 dB represents one pound control force per degree display error, and a remnant level of 0 dB represents a control power density level of one pound<sup>2</sup> per radian/second. All results pertain to single-axis, target-tracking tasks.

All frequency-response measurements are shown, regardless of the the standard error. In general, all frequency measurements below 8 rad/sec are "reliable" in terms of a low standard error. The reliability of measurements at higher frequencies fluctuated quite a bit from one condition to the next. In general, measurements at the highest SOS frequency should be regarded with caution.

Figure 3-7 shows that plant dynamics influenced primarily the pilot's response gain, the phase shift at mid frequencies, and the remnant spectrum in the roll axis. The gain and remnant differences reflect, for the most part, the different control gains provided for the two simulated aircraft. The pitch-axis data provided in Figure 3-8 show different frequency dependencies for the two vehicles as well as differences in overall gain and remnant levels. In particular, the "F-16" dynamics showed a more pronounced high-frequency peak in the gain response and a flatter phase response up to about 10 rad/sec than the "C-141" dynamics. Differences in pilot response across simulated vehicle and across axes of control were mimicked by the model.

As might be expected from the preceding discussion of closed-loop performance metrics, the effects of delay and simulation mode on pilot frequency response were substantially less than the effects of simulated aircraft dynamics. Figures 3-9 and 3-10 show that the qualitative effects of adding delay, in either axis, were to (1) slightly decrease pilot gain at low and mid frequencies, (2) decrease the frequency at which the gain curve peaks, (3) decrease phase lag (or increase phase lead) at mid frequencies, and (4) increase pilot remnant. As correctly predicted by the model, the effects of delay on gain and phase shift were more pronounced for the pitch axis response.

Figures 3-11 and 3-12 show some reduction in remnant and phase lag with the transition from ground to flight. The remnant curve may be interpreted as indicating a slightly wider response bandwidth for the in-flight tasks. The only sizeable effect predicted by the model (and not revealed in the data) was a mode-related difference in phase shift at the lowest measurement frequencies.

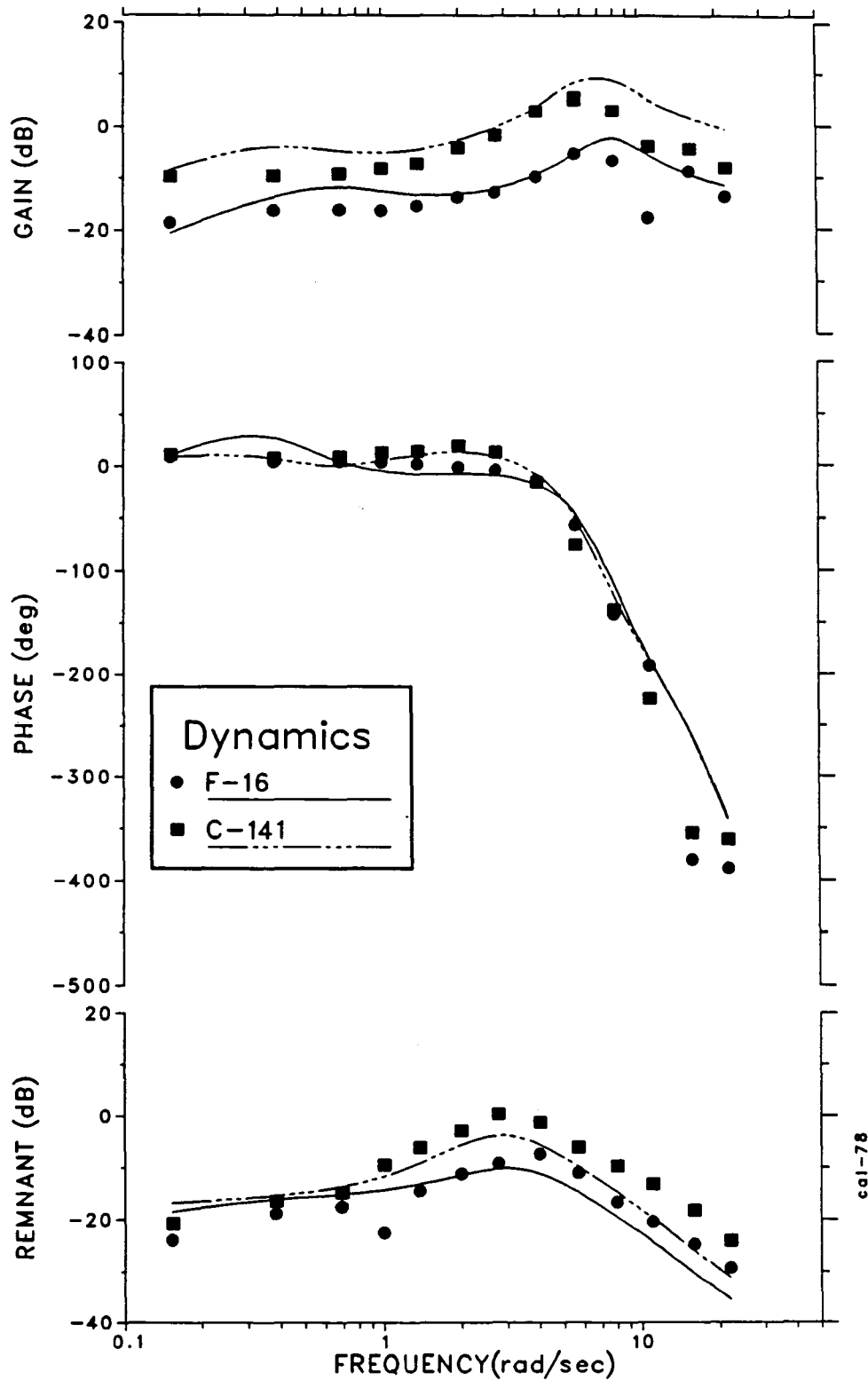


Figure 3-7: Effects of Dynamics on Pilot Frequency Response, Roll Axis  
Average of 3 subjects, 2 replications/subject.  
Single-axis, zero-delay, ground-based, target-tracking task.

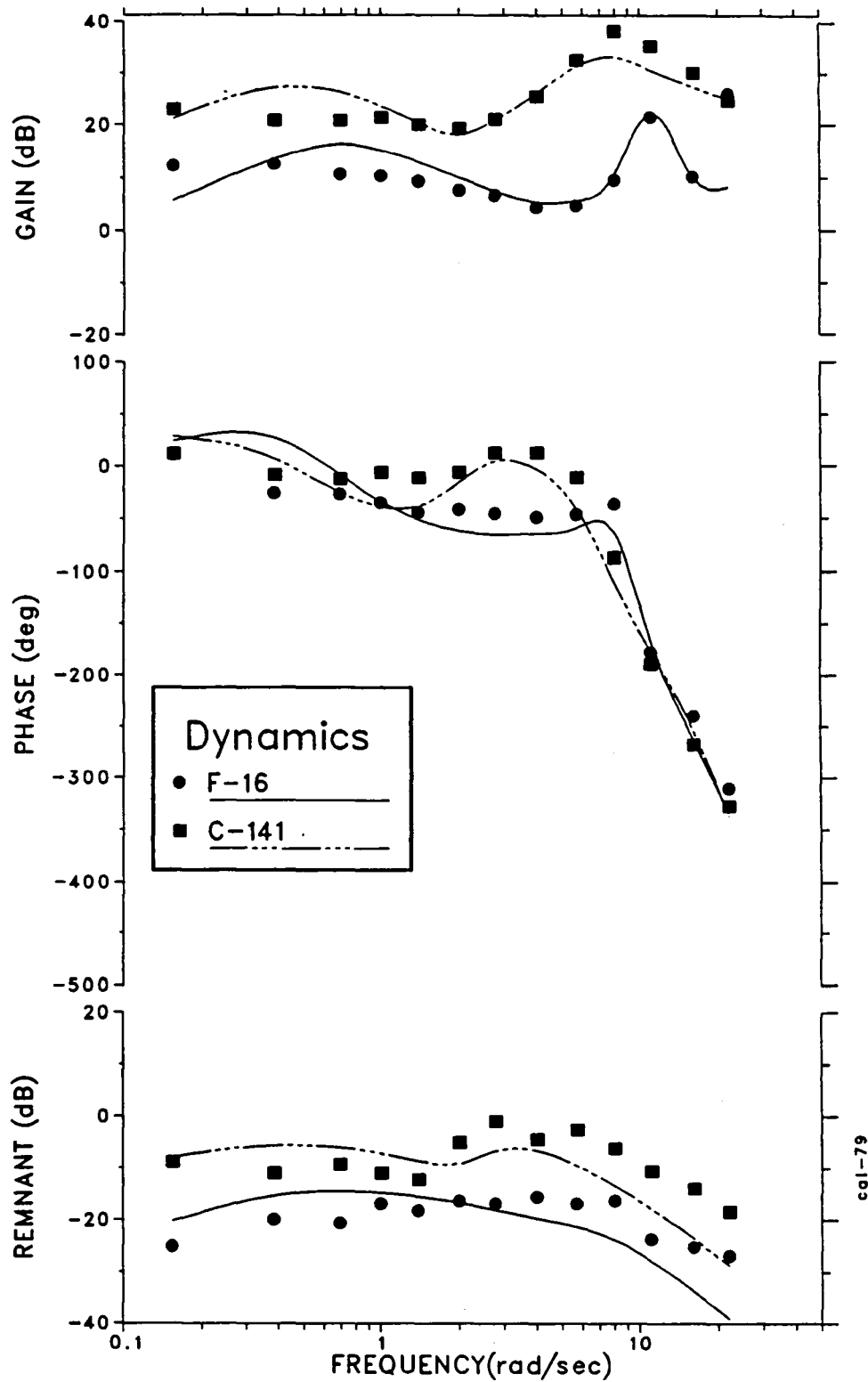


Figure 3-8: Effects of Dynamics on Pilot Frequency Response, Pitch Axis

Average of 3 subjects, 2 replications/subject.

Single-axis, zero-delay, ground-based, target-tracking task.

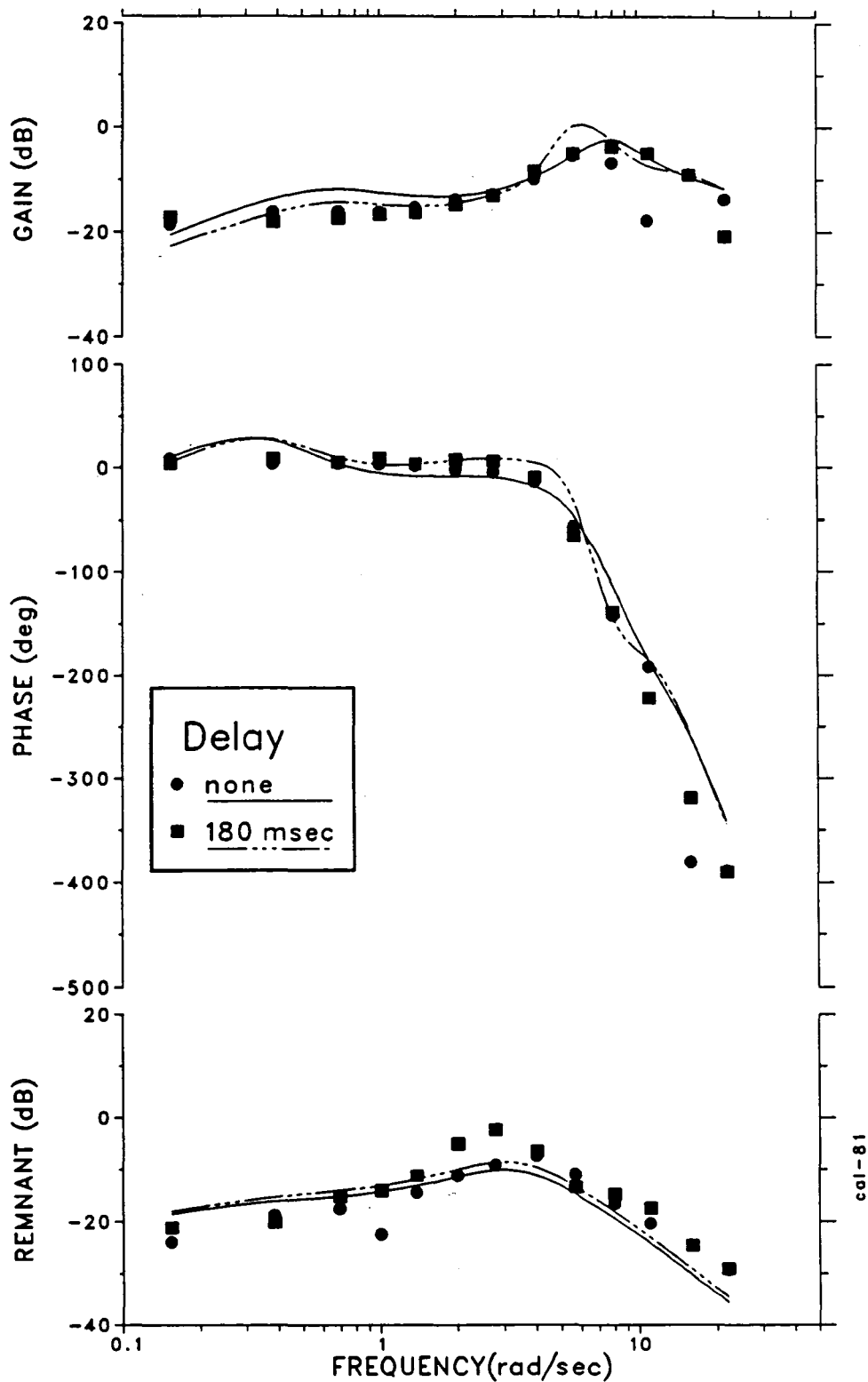


Figure 3-9: Effects of Delay on Pilot Frequency Response, Roll Axis  
Average of 3 subjects, 2 replications/subject.  
Single-axis, "F-16", ground-based, target-tracking task.

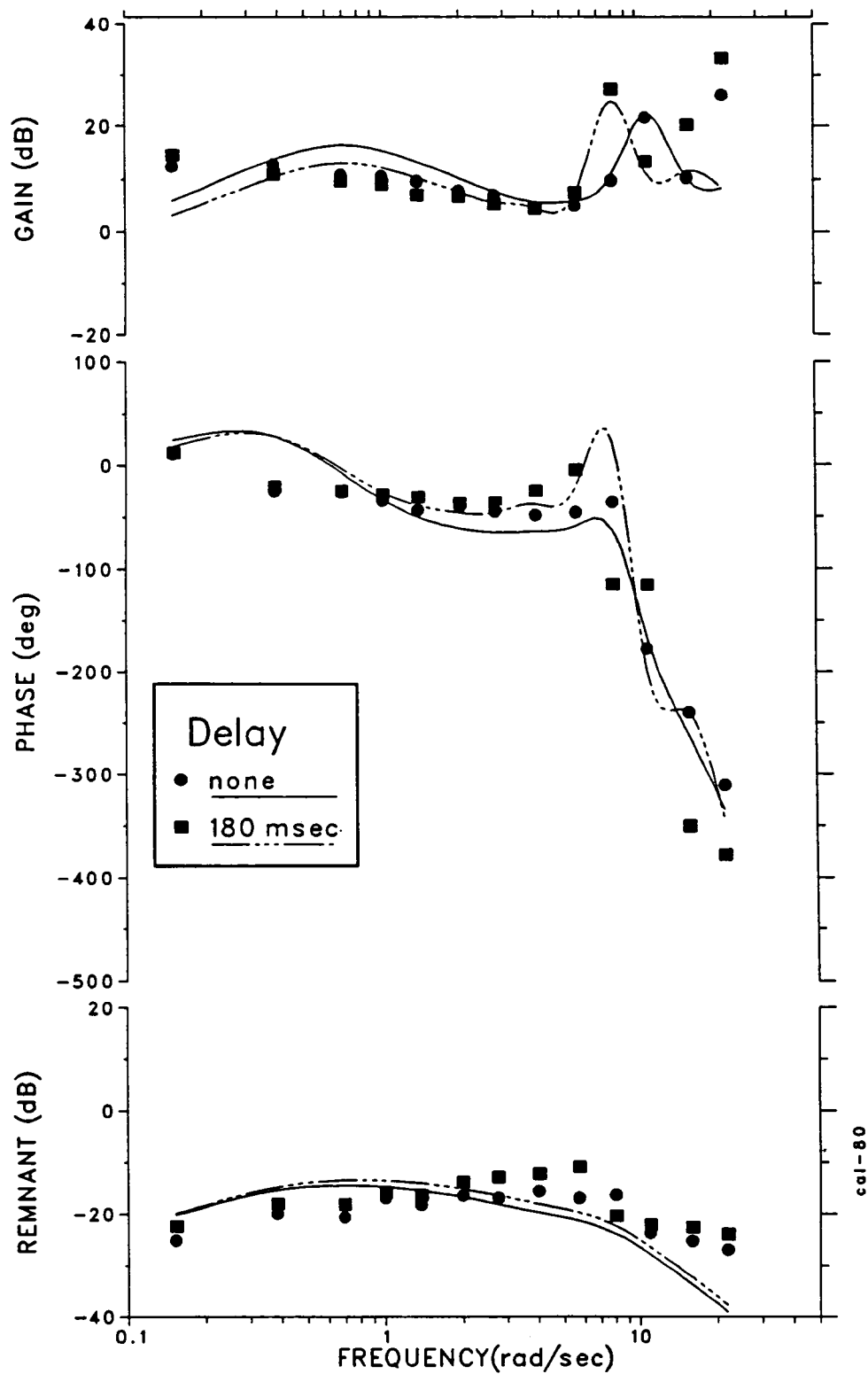


Figure 3-10: Effects of Delay on Pilot Frequency Response, Pitch Axis  
 Average of 3 subjects, 2 replications/subject.  
 Single-axis, "F-16", ground-based, target-tracking task.

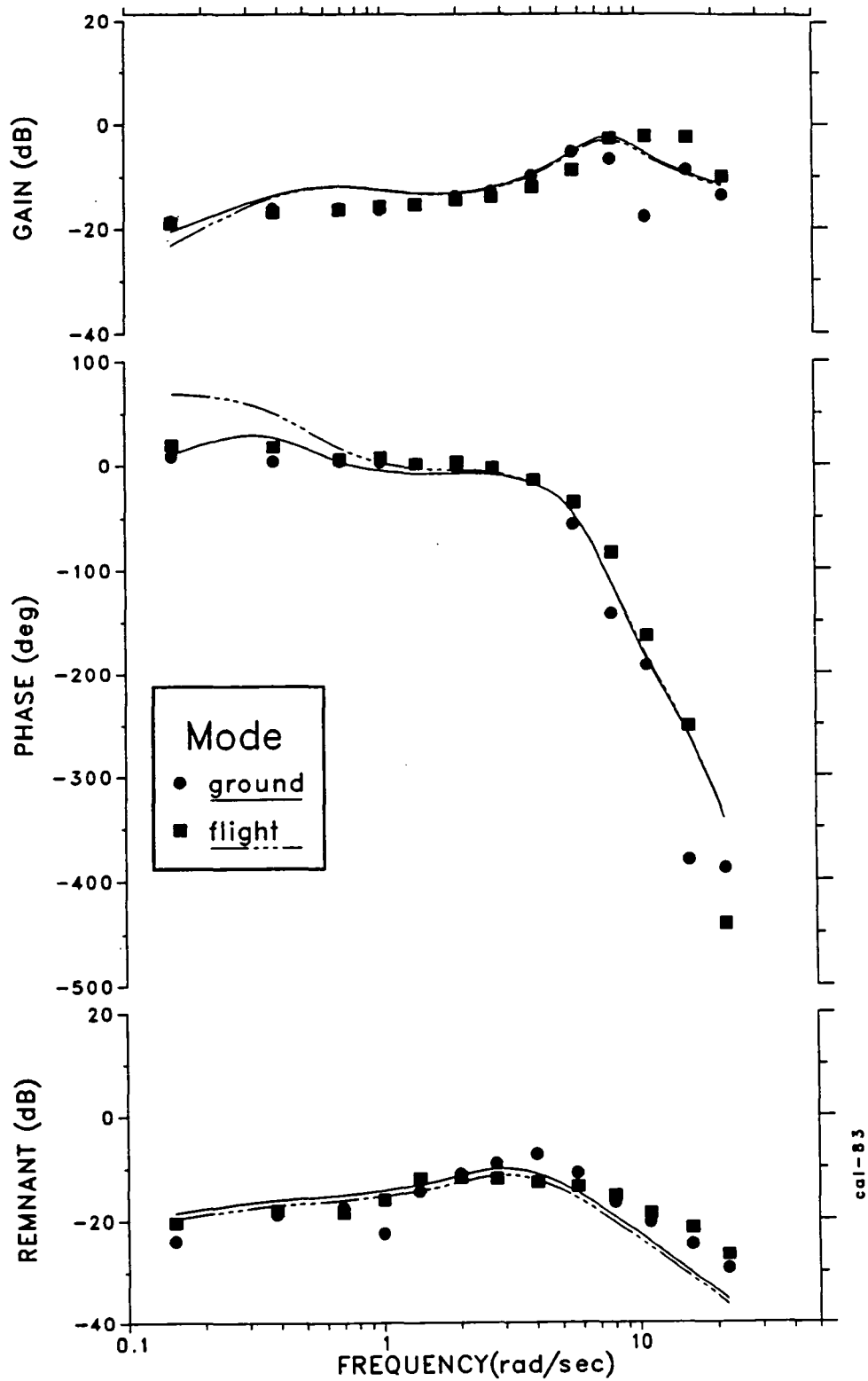


Figure 3-11: Effects of Simulator Mode on Pilot Frequency Response. Roll Axis  
 Average of 3 subjects, 2 replications/subject.  
 Single-axis, "F-16", zero-delay, target-tracking task.



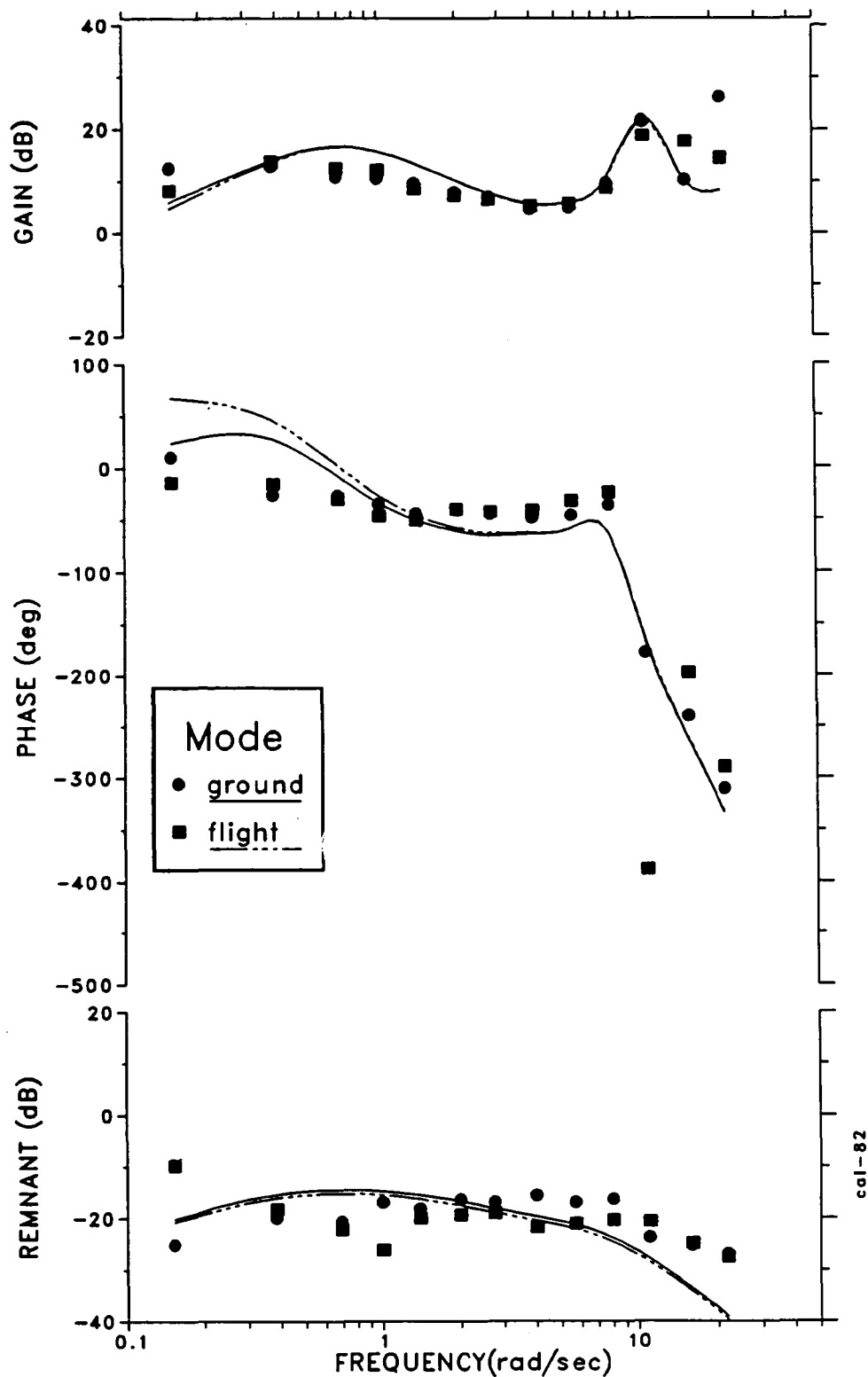


Figure 3-12: Effects of Simulator Mode on Pilot Frequency Response, Pitch Axis  
 Average of 3 subjects, 2 replications/subject.  
 Single-axis, "F-16", zero-delay, target-tracking task.

### 3.3 Nonlinear Analysis

The exploration of potential nonlinearities in the operator's response behavior was motivated by the unusually large values for the "motor time constant" and remnant-related parameters needed to provide an acceptable match to the average performance of the three test pilots. Examination of the individual performance of the three test pilots showed considerable differences between the best-performing pilot (in terms of minimizing rms roll error) and the other two pilots. These results prompted the suspicion that the response strategies of the two less-well-performing pilots might have contained significant nonlinearities, and that these nonlinearities might have resulted in the apparent reduced bandwidth and larger tracking error characteristic of these pilots.

Nonlinear analysis consisted of visual inspection of time histories, and statistical analysis of the probability densities, of one trial each for each of the three test pilots. The experimental condition represented by these trials was roll-axis tracking, ground-based simulation, "F-16" dynamics without additional time delay, with an external sum-of-sines target-command signal active in the roll axis only.

#### 3.3.1 Visual Inspection of Time Histories

Initial visual inspection of the pilot's output response ("stick") revealed substantial noise at the sampling frequency (50 Hz), which was felt to be due largely to the quantization of the stick amplitude imposed by the recording technique. In order to prevent this noise from masking important response trends, the stick signal was digitally filtered with a rectangular time window of 0.08 seconds. That is, each data point was replaced by the locally-averaged stick amplitude. This filtering operation significantly reduced high-frequency noise without apparent distortion to signal components within the bandwidth of man/machine response.

Time histories generated by the best-performing (Pilot A) and worst-performing (Pilot B) were inspected. Numerical printouts of the stick time histories were initially scanned for the appearances of intervals of little or no stick motion ("flat spots"). Five-second intervals containing these occurrences were then plotted for inspection.

In order to provide references against which to compare the experimental time histories, the following model

analysis was performed. First, the various performance metrics obtained from the two experimental trials were matched with the steady-state optimal control model (OCM). The simulation implementation of the OCM (Kleinman, Baron, and Berliner, 1977) was then used to generate stick time histories for the 5-second time segments of interest, using the appropriate Calspan experimental forcing function as the driving function. If the model were to match the pilot's linear characteristics perfectly, and if the effects of pilot remnant were negligible, the model and experimental stick time histories would be identical. Given the existence of remnant and the difficulty of a perfect match, the model-generated time histories are intended more as a qualitative reference. Specifically, one can determine whether or not the model predicts the response trends exhibited by the data.

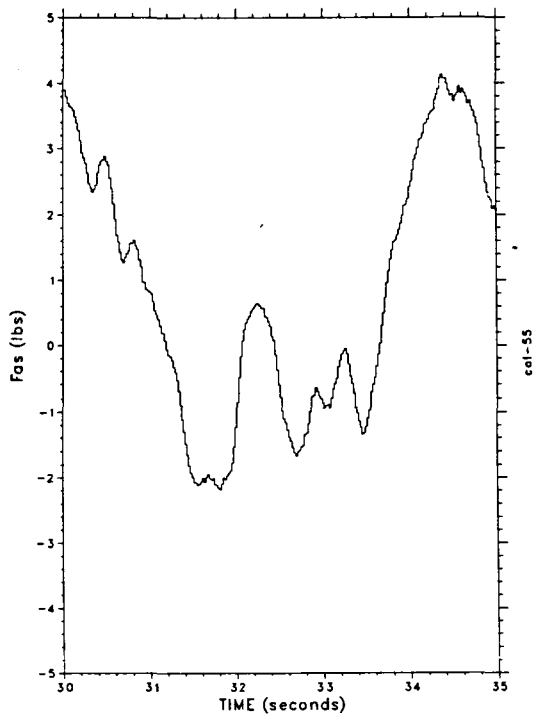
Table 3-2 shows the independent "pilot-related" model parameters that were found to provide an acceptable match to the data. Parameters shown for pilot A were initially selected on the basis of a recent BBN laboratory study on time-delay effects (Levison and Huggins, 1986). Only the motor time constant needed adjustment to provide a qualitatively acceptable match to the performance of Pilot A. To match the data of Pilot B, however, significant changes were made to remnant-related parameters, and the motor time constant was further increased to reflect the lower response bandwidth of this subject. The observation noise/signal ratio was increased by 4 dB, and a residual noise of 15 degrees -- representative of a visual or "indifference" threshold of 5 degrees -- was included. This residual noise value was consistent with the instructions given to the pilots, from which the pilots could infer that it was not necessary to maintain roll errors below 5 degrees. Residual noise was not needed to match the performance of Pilot A, however.

**Table 3-2: Independent Model Parameters**

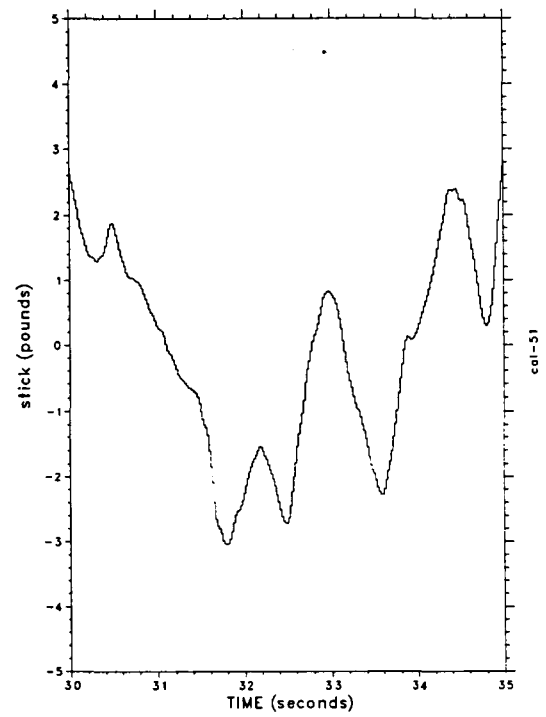
<b>Parameter</b>	<b>Pilot A</b>	<b>Pilot B</b>
<b>Motor Time Constant, sec</b>	<b>0.16</b>	<b>0.30</b>
<b>Operator Delay, sec</b>	<b>0.200</b>	<b>0.225</b>
<b>Residual Noise, Roll Angle, deg</b>	<b>0.0</b>	<b>15.0</b>
<b>Observation Noise/Signal Ratio, dB</b>	<b>-19.0</b>	<b>-15.0</b>
<b>Internal Motor N/S Ratio, dB</b>	<b>-44.0</b>	<b>-44.0</b>

Time histories for Pilot A are shown in Figure 3-13. Four plots are shown: (a) the experimental stick time history, (b) the stick time history predicted by the model, (c) the experimental error time history, and (d) the predicted error time history. Because the model analysis and experimental simulation used different sign conventions, the predicted error waveform shown in Figure 3-13d has been inverted to facilitate comparison with the other curves shown in Figure 3-13.

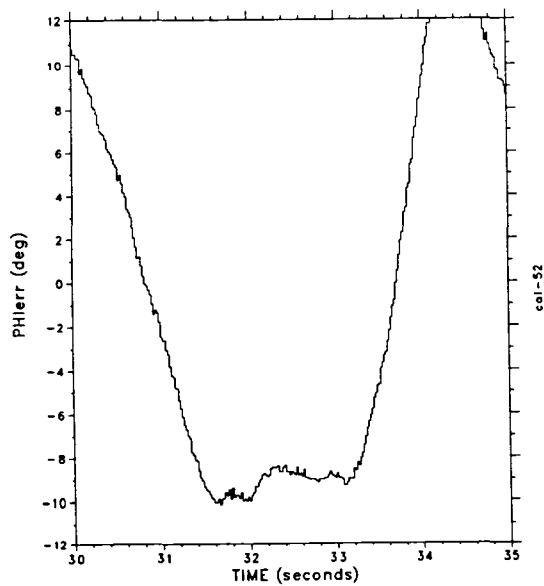
a) Stick (data)



b) Stick (model)



c) Error (data)



d) Error (model)

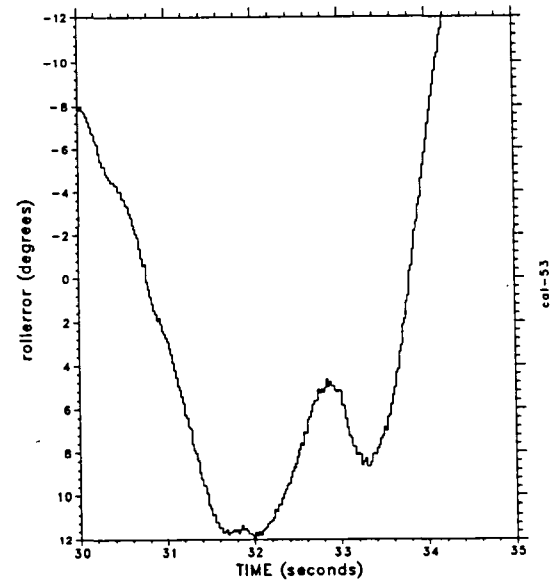


Figure 3-13: Time Histories for Pilot A

Comparison of Figures 3-13a and 3-13b shows that the predicted stick response is qualitatively (and to some extent, quantitatively) similar to the experimental stick response. As noted above, these waveforms cannot be expected to overlap exactly because of the stochastic response components (remnant) in both the experimental and predicted time histories. Nevertheless, one expects to see some correlation between the two because the same external forcing-function waveform has driven both the experimental and modeled systems.

The experimental stick response appears to show a tendency to remain relatively flat for an interval of about 0.5 seconds beginning around 31.5 seconds into the run. The model prediction does not support this tendency, suggesting evidence of a response nonlinearity. Note, however, that the experimental error time history (Figure 3-13c) also shows a relative flat spot over the same interval. If the pilot's response strategy were to act largely as a gain on roll error, this apparent pause in the pilot's response could be interpreted as a linear response to the error signal.

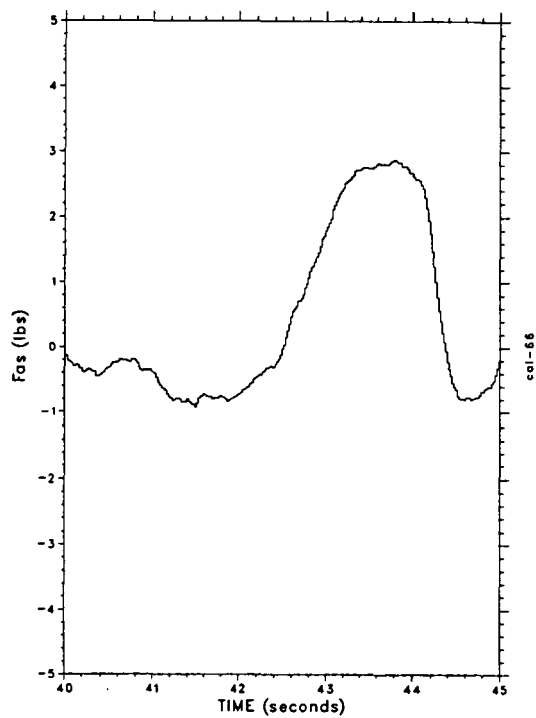
Stronger evidence of nonlinear response behavior is revealed by the time histories of Pilot B in Figure 3-14. Figure 3-14a shows a relative pause in response activity of about 1 second, beginning around 43.5 seconds into the run. The error signal plotted below does not reveal a similar flat spot, but rather a local maximum as the error reverses direction and heads toward zero. Furthermore, the model shows a more peaked response pattern (Figure 3-13b) in response to the same type of error pattern (Figure 3-13d) as found in the data. In this case, the pilot's response is less indicative of a linear response strategy and more suggestive of a "move-and-wait" strategy in which the pilot maintains a relatively constant control force that is sufficient to cause the error to begin to decrease. Other segments of this pilot's response time history (not shown here) revealed qualitatively similar patterns.

### 3.3.2 Statistical Analysis of Stick-Rate Amplitude

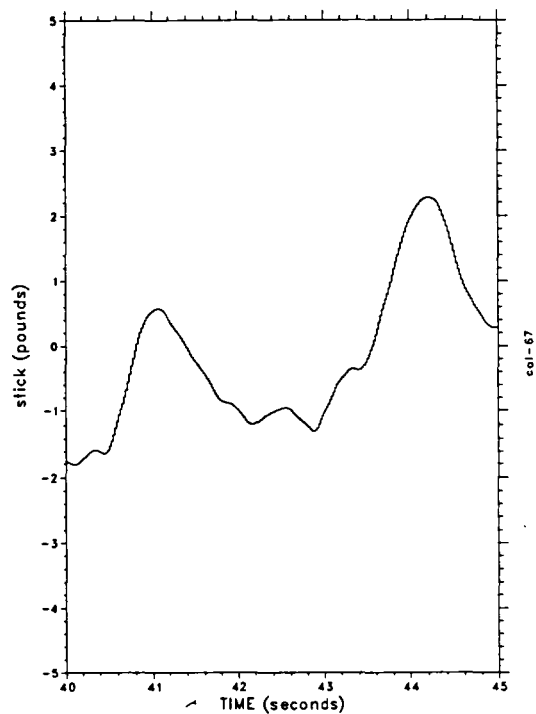
Objective analysis of selected time histories was performed to explore quantitative manifestations of the move-and-wait episodes subjectively found from visual inspection. Specifically, we tested the hypothesis that the stick rate would spend a larger fraction of time in the vicinity of zero than would a noisy but linearly responding system and that, therefore, the probability density of the stick rate amplitude would be significantly non-normal and would show a larger peak in the vicinity of zero amplitude than a Gaussian density function. Time histories from the three Calspan subjects were subjected to this type of analysis.

Computation of time-history statistics proceeded as follows:

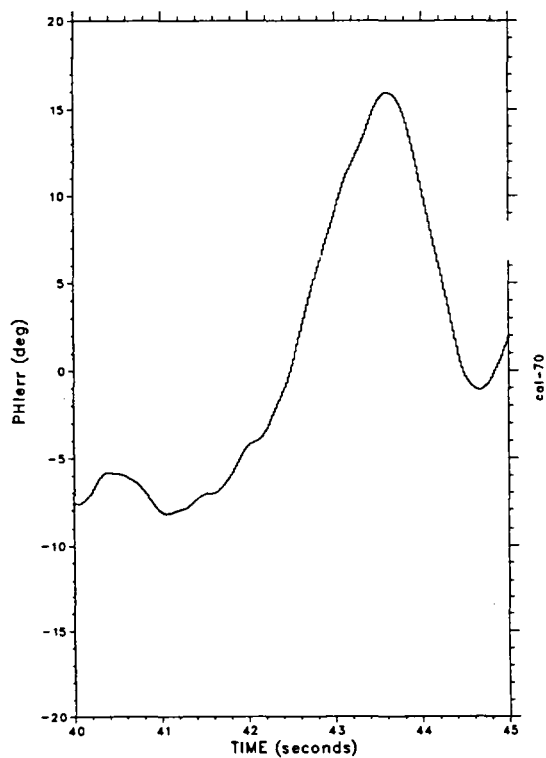
a) Stick (data)



b) Stick (model)



c) Error (data)



d) Error (model)

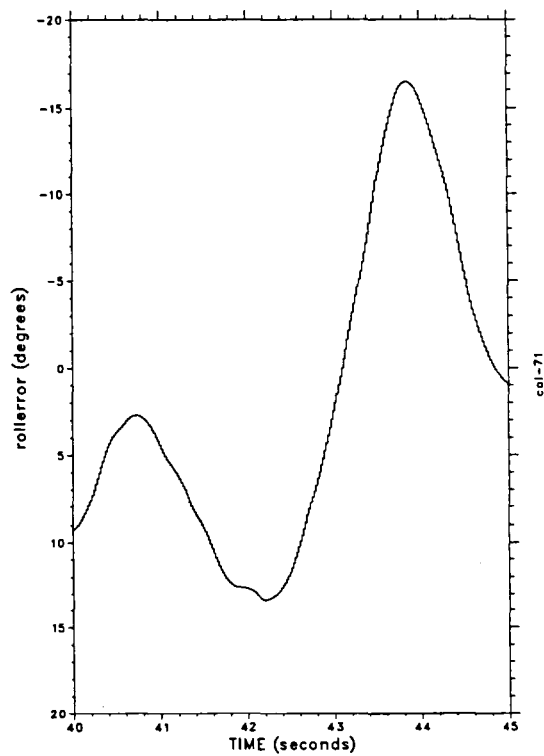


Figure 3-14: Time Histories for Pilot B

1. A stick-rate time history was constructed by computing, at each simulation sample interval, the first-difference of the stick time history divided by the simulation interval.
2. The stick-rate time history was smoothed with a rectangular window of 0.16 seconds. This smoothing window was increased from the 0.08 seconds used previously for plotting to minimize the effects of amplitude quantization on the recorded stick signal.
3. The smoothed signal was adjusted for the estimated mean and was normalized with respect to the estimated standard deviation to produce a normalized "z" variate. To minimize the effects of potential "outliers", the median was used as the estimated mean, and the standard deviation was estimated from the first and third quartile boundaries.
4. The amplitude distribution function was computed for the z variate at intervals of 0.2 for z values between -2.0 and 2.0.
5. A Kolmogorov-Smirnov (K-S) test was performed to determine the significance of the difference between the computed and theoretical normal distribution functions.
6. The probability density function was estimated from the distribution function as follows:

$$PDENS(Z) = CORR(Z) * (PDIST(Z+.2) - PDIST(Z-.2)) / 0.4$$

where PDIST is the cumulative distribution computed at Z intervals of 0.2 between -2.0 and 2.0, and CORR(Z) is the correction factor, computed as the ratio of the probability density of the normal curve divided by the density estimated from the normal distribution function according to the rule shown above. Because of "end effects", the probability density function was computed for z values between -1.8 and +1.8.

7. The rms difference between the computed probability density and the theoretically normal probability density was computed to provide a quantitative measure the deviation of the computed probability density from normality.

The above computations were performed on three time time histories, one for each of the test pilots. To provide a basis for comparison, identical analysis was performed on time histories obtained from the simulation model using the experimental forcing functions tracked by Pilots A and B.

Figure 3-15 shows that the simulated stick-rate time histories are nearly Gaussian. This subjective conclusion is confirmed by the first two rows of Table 3-3, which show no statistically significant deviation (i.e., alpha level > 0.05) from normality for the curve in Figure 3-15a and a marginally significant difference for the curve of Figure 3-15b. Thus, if the test pilots are linear but noisy responders as assumed in the OCM, we would expect the experimental stick-rate time histories to be nearly Gaussian.

Figure 3-16 shows that probability densities computed from the experimental results were less Gaussian than those computed from the model results. Furthermore, the deviation from normality was substantially less for the best-performing pilot (Pilot A) than for the other two pilots; this observation is confirmed by the rms deviations shown in the bottom three rows of Table 3-3.

Table 3-3: Amplitude Statistics for Stick Rate

Pilot	Alpha Level	RMS
A (simulated)	--	0.017
B (simulated)	0.05	0.022
A (experimental)	0.05	0.028
B (experimental)	0.01	0.058
C (experimental)	0.01	0.054

Alpha significance level determined from K-s test.

RMS indicates deviation of the probability density from the normal curve.

Figures 3-16a and 3-16c show trends consistent with a move-and-wait tendency in that the probability density is more peaked than the normal curve. This trend is particularly pronounced for Pilot C. The interpretation of the results for Pilot B is less clear; the curve suggests that this pilot tended to let his control input slowly drift during the intervals between significant control movements.

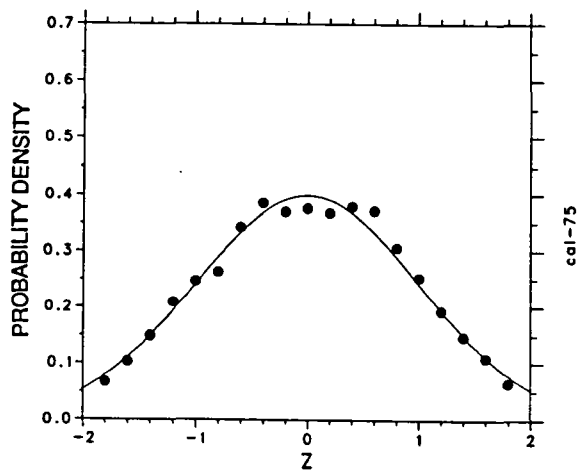
Because of the limited database explored, conclusions drawn from the foregoing analysis must be considered tentative at this stage. The results suggest the following trends:

1. Better-performing subjects, in terms of rms error minimization, tend to adopt a response strategy that is more nearly linear than subjects who perform less well.
2. Nonlinearities present in the operator's response strategy include move-and-wait episodes during which the operator maintains a relatively constant control force.

Additional study is needed to determine the extent to which these tentative conclusions can be generalized.



a) Pilot A



b) Pilot B

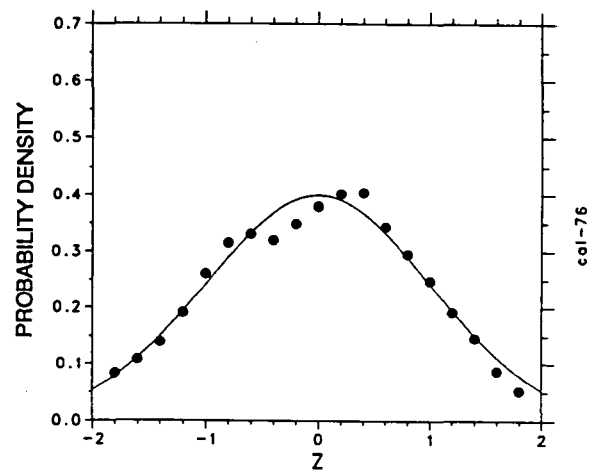
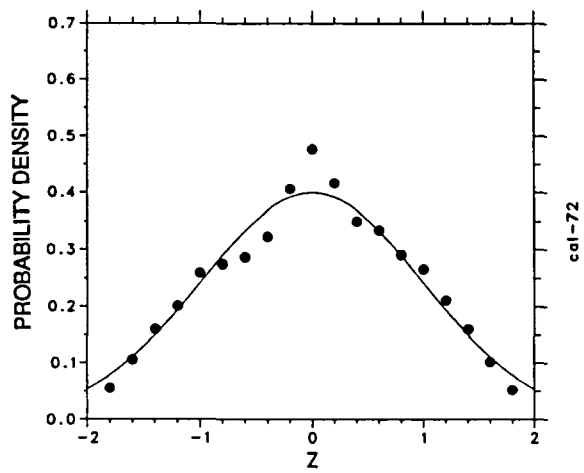
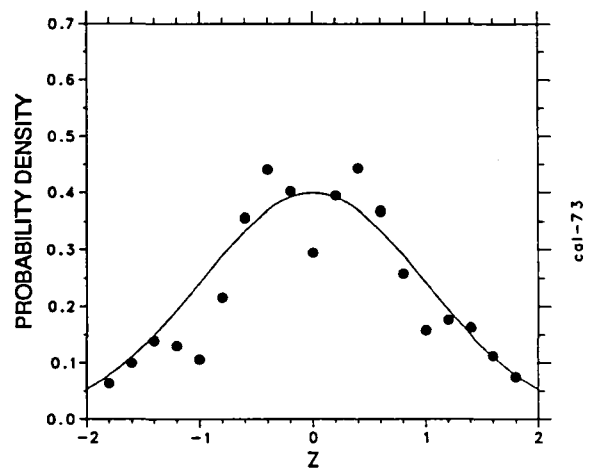


Figure 3-15: Probability Densities for Simulated Stick Rate

a) Pilot A



b) Pilot B



c) Pilot C

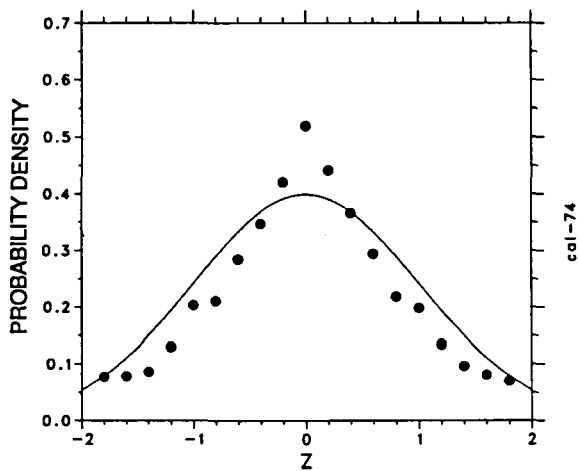


Figure 3-16: Probability Densities for Experimental Stick Rate



## 4. Discussion

To the extent that tracking error was analyzed by BBN, the trends predicted by pre-experiment model analysis were largely confirmed by the experimental study and replicated by post-experiment model analysis. Specifically,

- Addition of 180 msec delay to the flight-control system caused a modest increase (around 22%) in rms tracking error.
- Delay had a larger effect on performance with the simulated "F-16" than with the simulated "C-141".
- Error scores were, on the average, larger in the ground-based simulations than in the in-flight simulations, but ground/flight differences were relatively small (about 10% on the average).
- Performance trends were similar for the pitch and roll axes.
- The model, "calibrated" for the reference conditions in pitch and roll, replicated the important performance trends, but tended to somewhat underestimate the quantitative effects of delay and simulator mode.

The reader should note that all model results shown in this report were obtained with but two sets of model parameters: one set adjusted to jointly match roll-axis performance for the "F-16" and "C-141" in the single-axis, ground-based, zero-delay, target-tracking task, and one set adjusted to match pitch-axis performance.

The major discrepancy between experimental and model results concerned the differences between single-task and combined-task performance, where the predicted differences were substantially greater than those observed in most cases. As suggested earlier, we suspect this discrepancy was due largely to an error in modeling strategy. Recall that the "single-axis" tasks required the pilot to control the airplane in both pitch and roll in response to an external target input in only one axis. We modeled this situation by selecting observation noise parameters appropriate to true single-axis tracking (i.e., aircraft motion allowed in only one axis), and then accommodating the combined-axis task by doubling the observation noise/signal ratio to reflect an even split of attention between the two axes. With the advantage of hindsight, a better strategy would seem to be to assume that the pilot must share attention in a near-equal manner between the two axes whenever the two axes must be controlled, even if there is an explicit input in only one axis, as the cross-coupling induced by the pilot and/or the vehicle dynamics will effectively provide inputs in both axes.

It seems clear that selecting observation noise/signal ratios appropriate to combined-axis tracking for the so-called "single-axis" tasks would have allowed us to match the experimental results with "residual noise" levels closer to what would be associated with reasonable indifference thresholds. (Contract resources did not permit a repeat of the model analysis to test this hypothesis.)

On the basis of the results to date, we tentatively conclude that the OCM, properly calibrated, has the potential for interpolating the results of manned simulation studies for the type of steady-state flight tasks explored in the NT-33A experimental study. Although we have found the OCM to forecast performance trends with independent parameters selected entirely on the basis of previous results, we expect model application to be most reliable when the model is applied in conjunction with a manned simulation study, with parameters selected to match key reference conditions. Calibration against the specific data base will allow consideration factors specific to the simulation study, such as (1) the performance goals, motivation levels, and general piloting techniques of the specific test pilots; (2) the nature and amount of task-specific training received by the test pilots, and (3) other factors that account for the difference between laboratory tracking studies using over-trained college or high-school students and simulation studies using actual pilots performing representative flight tasks under constraints often avoided in the laboratory.

Tentative rules for calibrating the model are:

- Calibrate the model against the extreme conditions explored in the simulation study (e.g., widest- and narrowest-band vehicle dynamics, smallest and largest delay common to all vehicles, etc.).
- Adopt attention-related parameters appropriate to the number of axes controlled -- not to the number of axes containing external inputs.
- Where control-gains are not optimized for aggressive operations, test for the need of a specific penalty on control force to model the pilot's reluctance to generate large average control forces.
- Select residual noise parameters to reflect, at a minimum, perceptual resolution limitations and the pilot's lack of concern about reducing errors below some acceptable minimum.
- In general, follow the model-matching procedure described in Section 2.2 of this report.

The following areas of further study are suggested to develop and validate an integrated experimental and analytical method for determining simulator delay requirements:

1. Validate the Interpolative Capabilities of the Model. If the OCM is to be the analytic component of an experimental/analytic technique for exploring delay requirements, it must be shown capable of reliably interpolating between the conditions for which it is calibrated. The recent NT-33A simulation study has provided a data base suitable for a first test of model interpolation, as it contains data from two additional sets of aircraft dynamics (the "C-17" and "C-21" data), plus three additional time delays for each of these configurations. In addition, extrapolation from the target-tracking to the gust-disturbance tasks remains to be accomplished. This task, then, would not require additional manned simulations.
2. Extend OCM to Handling Qualities Predictions. Although this report has dealt entirely with objective performance metrics, the NT-33A data base also includes the traditional Cooper-Harper handling qualities metrics for each experimental condition. To the extent that pilot opinion will be considered an important indicator of simulator effectiveness, the utility of the OCM will be enhanced if it can interpolate handling qualities as well as performance data. We therefore suggest that an effort be made to explore a consistent method of model application that will mimic the NT-33A handling qualities data. This effort would build upon previous model applications in this area (Levison and Rickard, 1981).

3. Validate Experimental/Analytic Methodology. This task provides a demonstration of the combined experimental and analytic methods for exploring time delay requirements. We suggest that the extrapolative capabilities of the method be tested via model analysis and manned simulation studies of tasks other than the attitude-tracking tasks explored in the recent Calspan program. Future studies should include tasks that require path as well as attitude regulation: landing approach, in-flight refueling, and terrain-following are potential candidates.
4. Explore Criteria for Temporal Fidelity Requirements. The discussion so far has dealt with measurement and prediction of the influence of delay on objective and subjective performance, but it has not directly addressed the central issue of how much simulator delay (more generally, temporal distortion) can be tolerated in a given simulator application. This study area would most likely involve a significant manned simulation component, particularly if training transfer were to be explored; innovative modeling approaches might also be required. One possible approach to this task would be to develop a backward chaining of requirements, where we proceed from requirements in terms of the simulator application (e.g., the tolerable increments in training time), to requirements in terms of objective performance measures and pilot ratings, to requirements in terms of allowable delays.



## 1. References

1. Kleinman, D.L., Baron, S., and Berliner, J.E., "MCARLO: a Computer Program for Generating Monte-Carlo Trajectories in a Time-Varying Man/Machine Control Task", Technical Report TD-CR-77-2, U.S. Army Missile Research and Development Command, Redstone Arsenal, Alabama, June 10, 1977.
2. Levison, W.H., "Effects of Whole-Body Motion Simulation on Flight Skill Development", Report No. 4645, Bolt Beranek and Newman, Inc., Cambridge, MA, October 1981. ADA 111-115
3. Levison, W.H., "Effects of Control Stick Parameters on Human Controller Response", Report No. 5510, Bolt Beranek and Newman Inc., Cambridge, MA, January 1984.
4. Levison, W.H., and Baron, S., "F-14 Modeling Study: Final Report", NASA-CR-172336, NASA Langley Research Center, Langley, VA, May 1984.
5. Levison, W.H., "Some Computational Techniques for Estimating Human Operator Describing Functions", Proc. of the Twenty-first Annual Conference on Manual Control, NASA Conference Publication 2428, pp. 31.1-31.21, May 1986.
6. Levison, W.H. and A.W.F. Huggins, "Modeling the Effects of Delays and Lags on Tracking Performance", Report number 6245, BBN Laboratories Incorporated, Cambridge, MA, June 1986.
7. Levison, W.H., Junker, A.M., and Kenner, K.K., "Descriptive Linear Modeling of Steady-State Visual Evoked Response", Proc. of the Twenty-first Annual Conference on Manual Control, NASA Conference Publication 2428, pp. 1.1-1.16, May 1986.
8. Levison, W.H., and Papazian, B., "Pre-Experiment Model Analysis in Support of the NT-33A Ground Simulator Time Delay Study", Technical Memorandum EPD-86-6, Bolt Beranek and Newman Inc., Cambridge, MA, April 11, 1986.
9. Levison, W.H. and Rickard, W.W., "Closed-Loop Criteria for Assessing Longitudinal-Axis Handling Qualities of Transports in Final Approach," Proc. of the AIAA Guidance and Control Conference, Albuquerque, NM, August 19-21, 1981.
10. Levison, W.H. and Warren, R., "Use of Linear Perspective Scene Cues in a Simulated Height Regulation Task," Proc. of the Twentieth Annual Conference on Manual Control, NASA Conference Publication 2341, Volume I, pp. 467-490, June 1984.
11. Repperger, D.W. and Levison, W.H., "Effects of Control Stick Parameters on Human Controller Response", Proc. of the Twentieth Annual Conference on Manual Control, NASA Conference Publication 2341, Volume I, pp. 157-166, June 1984.
12. Zacharias, G.L. and W.H. Levison, "A Performance Analyzer for Identifying Changes in Human Operator Tracking Strategies", AMRL-TR-79-17, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, March 1979.





## Appendix A

This Appendix contains population means and standard errors for tracking error and stick force SD scores for the conditions explored in the BBN analysis.

Table A-1: Experimental Roll-Axis SD Scores

Average of 3 subjects, 2 replications/subject

Vehicle	Sim. Mode	Delay	Roll Error		Stick Force		Stick Rate	
			Mean	S.E.	Mean	S.E.	Mean	S.E.
a) 1-axis Target Input								
"F-16"	Ground	0	8.23	0.90	1.53	0.16	5.14	1.06
		180	10.3	1.16	1.80	0.16	5.98	0.98
	Flight	0	7.40	1.24	1.30	0.16	5.76	1.33
		180	8.39	1.03	1.59	0.21	6.22	1.83
"C-141"	Ground	0	4.89	0.53	2.63	0.29	18.2	1.35
		180	6.03	0.73	3.22	0.68	13.0	2.43
	Flight	0	4.97	0.98	1.89	0.29	8.86	2.54
		180	5.66	0.95	2.43	0.18	13.3	1.35
b) 2-axis Target Input								
"F-16"	Ground	0	8.56	1.36	1.45	0.16	4.39	1.08
		180	9.76	1.10	1.77	0.20	6.14	1.58
"C-141"	Ground	0	5.41	0.54	2.46	0.22	8.77	1.55
		180	6.65	0.78	2.85	0.28	11.4	3.17
c) 2-axis Disturbance Input								
"F-16"	Ground	0	4.12	0.58	0.61	0.15	3.22	1.15
		180	4.49	0.78	0.81	0.24	4.62	2.16
"C-141"	Ground	0	5.35	0.54	2.83	0.41	13.0	3.03
		180	6.44	0.72	3.26	0.54	15.2	5.89

**Table A-2: Experimental Pitch-Axis SD Scores**

**Average of 3 subjects, 2 replications/subject.**

Vehicle	Sim. Mode	Delay	Pitch Error		Stick Force		Stick Rate	
			Mean	S.E.	Mean	S.E.	Mean	S.E.
a) 1-axis Target Input								
"F-16"	Ground	0	0.352	0.046	1.08	0.05	4.07	0.42
		180	0.451	0.050	1.22	0.04	5.82	1.06
	Flight	0	0.290	0.039	1.01	0.18	3.96	0.90
		180	0.383	0.047	1.16	0.16	4.90	0.75
"C-141"	Ground	0	0.295	0.043	3.60	0.14	14.8	2.89
		180	0.356	0.039	4.33	0.22	20.4	6.97
	Flight	0	0.284	0.048	3.71	1.19	14.9	3.75
		180	0.352	0.044	4.38	0.81	31.0	7.95
b) 2-axis Target Input								
"F-16"	Ground	0	0.366	0.036	1.34	0.07	6.92	0.61
		180	0.498	0.033	1.57	0.13	10.1	3.65
"C-141"	Ground	0	0.304	0.037	4.67	0.35	20.7	3.94
		180	0.425	0.047	5.46	0.48	27.8	10.1
c) 2-axis Disturbance Input								
"F-16"	Ground	0	0.221	0.011	0.635	0.049	6.45	1.09
		180	0.267	0.019	0.702	0.168	7.43	3.22
"C-141"	Ground	0	0.325	0.109	3.58	0.96	24.9	12.1
		180	0.401	0.123	4.42	1.07	30.0	13.2

Table A-3: Model-Generated Roll-Axis SD Scores

Vehicle	Sim. Mode	Delay	Roll Error	Stick Force	Stick Rate
a) 1-axis Target Input					
"F-16"	Ground	0	8.26	1.47	4.95
		180	9.63	1.57	5.48
	Flight	0	7.81	1.36	4.50
		180	9.04	1.42	4.89
"C-141"	Ground	0	5.13	2.43	8.45
		180	5.87	2.63	9.56
	Flight	0	4.75	2.19	7.48
		180	5.37	2.36	8.29
b) 2-axis Target Input					
"F-16"	Ground	0	10.6	1.51	5.18
		180			
"C-141"	Ground	0	7.01	2.59	9.17
		180			
c) 2-axis Disturbance Input					
"F-16"	Ground	0			
		180			
"C-141"	Ground	0			
		180			

Table A-4: Model Predicted Pitch-Axis SD Scores

Vehicle	Sim. Mode	Delay	Pitch Error	Stick Force	Stick Rate
a) 1-axis Target Input					
"F-16"	Ground	0	0.353	1.01	2.70
		180	0.431	1.04	3.05
	Flight	0	0.339	0.974	2.53
		180	0.411	0.985	2.82
"C-141"	Ground	0	0.283	3.51	9.27
		180	0.332	3.63	1.02
	Flight	0	0.276	3.36	8.69
		180	0.322	3.43	9.48
b) 2-axis Target Input					
"F-16"	Ground	0	0.452	1.01	2.81
		180			
"C-141"	Ground	0	0.357	3.54	9.67
		180			
c) 2-axis Disturbance Input					
"F-16"	Ground	0			
		180			
"C-141"	Ground	0			
		180			



## Report Documentation Page

1. Report No.  NASA CR-4164		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle  F-14 Modeling Study — Final Report				5. Report Date  July 1988	
				6. Performing Organization Code	
7. Author(s)  William H. Levison				8. Performing Organization Report No.  BBN Report No. 6579	
				10. Work Unit No. 505-35-33-01	
9. Performing Organization Name and Address BBN Laboratories Incorporated 10 Moulton Street Cambridge, MA 02238				11. Contract or Grant No.  NAS1-17648	
				13. Type of Report and Period Covered  Contractor Report	
12. Sponsoring Agency Name and Address  National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665-5225				14. Sponsoring Agency Code	
15. Supplementary Notes  Langley Technical Monitor: Burnell T. McKissick					
16. Abstract  This study explored application of a closed-loop pilot/simulator model to the analysis of some simulator fidelity issues. The model was applied to two data bases (1) a NASA ground-based simulation of an air-to-air tracking task in which non-visual cuing devices were explored, and (2) a ground-based and in-flight study performed by the Calspan Corporation to explore the effects of simulator delay on attitude-tracking performance. The model predicted the major performance trends obtained in both studies. A combined analytical and experimental procedure for exploring simulator fidelity issues is outlined.					
17. Key Words (Suggested by Author(s))  Simulator fidelity issues Ground-based In-flight simulation Closed-loop pilot/simulator model			18. Distribution Statement  Unclassified - Unlimited   Subject Category 08		
19. Security Classif. (of this report)  Unclassified		20. Security Classif. (of this page)  Unclassified		21. No. of pages  56	
				22. Price  A04	

**End of Document**